A Softwarized and MEC-Enabled Protocol Architecture Supporting Consumer Mobility in Information-Centric Networks

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ABSTRACT

Information-Centric Networking emerged as a powerful enabling technology for the provisioning of scalable and efficient real-time services in Future Internet, mobile architectures, and multi-hop wireless mesh networks. To serve mobile consumers, most of scientific contributions suggest to extend the information-centric communication primitives by means of a pull-based methodology, according to which the mobile consumer issues pending requests every time it reaches a new network attachment point. This approach, however, generates two important shortcomings. First, the requests delivered before the handover will generate stale paths with wrong forwarding information in their network routers. As a consequence, some new contents will be delivered also to previous locations, thus wasting bandwidth. Second, during handovers, mobile consumers may miss some contents released in real-time and lose the synchronization with the remote producer. In order to solve these issues, this work conceives a novel protocol architecture that successfully integrates and properly customizes the key functionalities of Information-Centric Networking, Multi-access Edge Computing, and Software Defined Networking paradigms. Specifically, the designed approach envisages that (1) Multi-access Edge Computing assists mobile consumers in retrieving data, while transparently managing the information-centric communication primitives and recovering the synchronization with the remote producer after the handover, (2) Software-Defined Controllers dynamically configure forwarding functionalities, and (3) Information-Centric Networking enables efficient data dissemination and delivers network control instructions. The impact of the devised protocol architecture on the communication overhead is analytically formulated and evaluated in scenarios with different topology, mobility, application settings, and number of mobile consumers. The comparison with respect to the pure Information-Centric Networking deployment demonstrates that the proposed solution ensures a reduction of the communication overhead up to 99.99% on the data plane, an overall bandwidth saving up to 99.93%, and a not negligible memory saving in intermediary routers. At the same time, the adoption of information-centric communication primitives for the control plane achieves an overhead reduction ranging from 29.36% to 51.13% with respect to an implementation based on the conventional OpenFlow protocol.

1. Introduction

Today, Information-Centric Networking (ICN) [1, 2] is considered a well-established technology able to offer advanced, secure, scalable, and efficient services in a wide range of network deployments, such as Future Internet [3–7], mobile architectures [8–14], and multi-hop wireless mesh networks [15, 16]. Nevertheless, the provisioning of real-time applications (such as real-time generated content from websites [17] and live-streaming videos [18, 19], or data requested by robot consumers for remote control [20] and local decisions [21–23]) to mobile consumers still represents a challenging research topic that necessitates a thorough investigation. With reference to pure ICN deployments, the majority of works published in the scientific literature assumes to manage consumer mobility through a pull-based approach: every time the consumer moves to a new network attachment point, it re-issues the set of pending requests [11, 12, 24, 25]. This basic solution, however, generates two important shortcomings, which significantly compromise the network performance and the quality of service experienced by end users. As deeply investigated in [24], in fact, the requests delivered just before the handover leave into the network wrong forwarding information, lead to the dissemination of unuseful data to stale destinations, and inevitably generate a waste of bandwidth. On the other hand, as outlined in a preliminary study presented in [26], during the handover, mobile consumers may miss contents released in real-time and lose the synchronization with the remote producer. Other sophisticated approaches for consumer

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mobility, including tunnel-based, update-based, and locator/identifier separation schemes [27–29], are still affected by these problems and, in some cases, may magnify their negative impact on the performance (see Section 2 for more details).

Recent studies proposed to exploit Software-Defined Networking (SDN) [3–7] and Multi-access Edge Computing (MEC) [30–32] technologies to boost the potential of ICN paradigm. Thanks to its native ability to control forwarding functionalities, SDN can be adopted to manage mobility [33–35], also in ICN networks [8–14]. Unfortunately, most of the available contributions focus on producer mobility. Few works addressing consumer mobility propose proactive methodologies that seamlessly deliver requested contents towards the expected new positions of mobile users [11–14]. Moreover, they do not solve the issues related to the presence of wrong forwarding rules and the loss of synchronization with the remote producer. At the same time, all the contributions integrating SDN facilities in ICN deployments assume to use the conventional OpenFlow protocol for network programmability purposes, despite the skepticism against this de facto standard highlighted by many research initiatives working on novel approaches, like Protocol Oblivious Forwarding (POF) and Next Generation SDN (NG-SDN) [36–39].

On the other hand, MEC capabilities can further improve ICN and SDN functionalities, as discussed in [25, 30–32, 40–46]. But, also in this case, available studies do not explore the issues emerged from [24] and [26].

To bridge this gap, the work discussed herein intends to significantly extend the current state of the art by conceiving a novel protocol architecture that successfully integrates and properly customizes the key functionalities of ICN, MEC, and SDN, solves the challenging drawbacks generated by consumer mobility, and (more in general) improves the overall network control and performance. The devised solution is very general and can be applied to a wide range of network deployments. However, by considering the recent interests of the scientific community working in this area, the discussion presented herein focuses the attention on multi-hop wireless mesh networks. Specifically, the reference scenario embraces many network attachment points randomly located within a given geographical area, providing wireless connectivity to mobile consumers, through heterogeneous communication technologies (i.e., multi-access). Each network attachment point hosts a MEC entity, which assists mobile consumers in the data retrieving process. The consumer interacts with its reference MEC entity according to the publish-subscribe mechanism. Once received a subscription request from the mobile consumer, the MEC entity starts retrieving the contents generated (in real-time) by the producer by using a request-response communication pattern. Every time the mobile consumer attaches to a network attachment point, the new reference MEC entity recovers the synchronization with the remote producer and contacts the Software-Defined Controller (SDC) for dynamically deleting wrong forwarding information still configured in intermediary nodes of the multi-hop wireless mesh network. The latter functionality is practically implemented through two novel procedures, namely Neighbor Inspection and Router Inspection. Moreover, POF protocol is adopted to deliver control messages through information-centric communication primitives. Indeed, differently from the current state of the art, the conceived protocol architecture leverages ICN for both the data plane and the control plane.

The impact of the conceived protocol architecture to the communication overhead is analytically formulated and numerically evaluated in scenarios with different topology, mobility, and application settings, for various number of mobile consumers. The study evaluates several Key Performance Indicators (KPIs), including average communication overhead on the data plane, average communication overhead on the control plane, average overhead reduction achieved with respect to reference approaches exploiting the baseline pull-based strategy (such as [9–14, 30, 31]), as well as the bandwidth and memory savings obtained by deleting wrong forwarding information in intermediary network routers. Obtained results demonstrate that the proposed approach achieves a reduction of the communication overhead up to 99.99% on the data plane, an overall bandwidth saving up to 99.93%, and a not negligible memory saving in intermediary routers. At the same time, the adoption of information-centric communication primitives for the control plane ensures an overhead reduction ranging from 29.36% to 51.13% with respect to an implementation based on the conventional OpenFlow protocol. These benefits are generally confirmed also in the presence of multiple consumers. Only in extreme scenarios with a small network size, low traffic load, and very high number of mobile consumers asking for the same real-time contents, the amount of bandwidth consumed on the control plane appears comparable with the waste of bandwidth avoided on the data plane. Nevertheless, the distinctive aspect of the proposed protocol architecture is still evident: the proposed solution jointly addresses network control and communication functionalities with a transparent and flexible (because fully information-centric) methodology. The rest of the work is organized as in what follows. Section 2 discusses the state of the art on ICN, SDN, and MEC paradigms, by posing particular attention to the contributions focusing on consumer mobility. Section 3 and Section 4 present the conceived protocol architecture and formulate the analytical models describing the communication overhead it produces, respectively. Section 5 illustrates numerical results. Finally, Section 6 draws the conclusions of the work and summarizes future research activities.

2. Analysis of the state of the art

At the time of this writing, different state of the art contributions addressed consumer mobility and solve the service disruption issue. This section intends to review the solutions exploiting ICN, SDN, and MEC technologies, as well as emerging network architectures based on their integration. The proposed storyline will provide a clear idea of open issues not yet considered by the current scientific literature, which, instead, are of interest for the solution discussed in this work.

2.1. ICN and solutions for the consumer mobility

ICN represents a revolutionary communication paradigm for the Future Internet [1]. Differently from the current Internet, it poses the attention on contents to be exchanged (i.e., information-centric logic), instead of the need to establish an end-to-end connection between communicating peers (i.e., host-centric logic). The key idea adopted by ICN is that unique names (frequently referred to as content names) identify self-secured contents and drives forwarding operations for both requests and corresponding responses. The information-centric approach is implemented in PURSUIT, DONA, Named Data Networking (NDN), and CONET architectures [2], which generally differ for the adopted content namespace, communication scheme, and control operations. Without loss of generality, this work focuses on NDN, which represents a widely accepted architecture based on the ICN paradigm [1, 47]. However, with few adjustments, the results of this work may be extended to other architectures as well.

In NDN, the communication follows a receiver-driven and request-response scheme: the consumer requests a content by issuing an Interest packet; the network implements routing-by-name, caching, and request aggregation mechanisms and forwards back the requested content through a Data packet. To this end, each NDN router implements three data structures, that are: Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB). The CS of intermediate routers stores cached contents. The PIT table keeps track of received requests (i.e., Interest packets) and the network interfaces they came from. Requests for the same content are aggregated herein within a single PIT entry. This information is used to forward Data packets back to consumers across the same path of the request. Finally, the FIB table implements forwarding rules, based on the Longest Prefix Matching criteria.

NDN often handles the mobility of consumers by means of a pull-based approach [11, 12, 24, 25]. A mobile consumer initially establishes a multi-hop communication path with the remote producer and requests the contents of its interest. When it moves to a new network attachment point, the consumer sends again the pending Interest packets from its updated location. Despite this baseline solution appears simple and effective [2], it generates two important drawbacks [24, 26]. First, every time a consumer changes its position, a multi-hop communication path is created between the new attachment point and the producer. The path established before the handover, namely stale path, remains active until the related PIT entries expire. Moreover, it may remain active also after the handover process, or at the end of a long period of network detachment experienced by mobile consumers in the case of non-overlapping cells. As a consequence, contents requested before the handover could be forwarded to the old location due to wrong information stored in stale disjoint routers, thus bringing to an unexpected waste of bandwidth (see Fig. 1) [24]. Second, during the handover, the consumer is unable to receive content updates. In addition, after the handover, it is also unaware of what are the latest contents available. Consequently, it is not capable to resume the data exchange with the remote producer for real-time contents (i.e., the synchronization between consumer and producer is lost) [26]. Of course, the negative impact of this issue increases in scenarios with non-overlapping cells, where the mobile consumer may experience a long period of network detachment.

More sophisticated approaches for consumer mobility are: tunnel-based, update-based, and locator/identifier separation [27–29]. The tunnel-based scheme leverages the triangular routing, as implemented by Mobile IP [48, 49]. This means that, when a mobile consumer moves to a new access network, it sends a binding update to its previous attachment point. Then, all packets reaching the old position are encapsulated and routed towards the new one. Optionally, anchor points can be created on demand during the handover to act as a proxy between the mobile consumer and the network [50, 51]. Update-based approaches intend to dynamically modify PIT and FIB tables according to the consumers' mobility. These updates may be triggered and/or implemented by mobile consumers, network nodes, or resource handlers [52]. Finally, the locator/identifier separation-based approach assigns a locator to each router and supposes to explain, directly into the content name, the locators of routers through which forward the data. This way, packets are forwarded across locators, without a priori knowledge of the consumer position [53]. This approach also

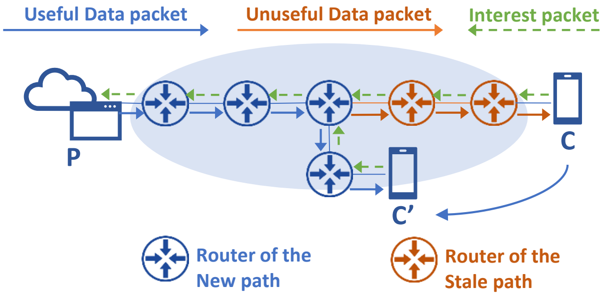

Figure 1: Communication overhead due to stale paths, as described in [24].

enables proactive caching mechanisms [54–58]. However, proactive and tunnel-based approaches still present some problems. On the one hand, proactive approaches may solicit the forwarding of the requested contents to all nearby locations, thus producing a higher number of stale paths. Likewise, if contents are proactively forwarded to a single location (i.e., following a prediction algorithm), a new stale path is created if the prediction is wrong. On the other hand, tunnel-based approaches generate longer stale paths if mobile consumers are no longer interested in real-time contents previously requested. Furthermore, update-based approaches require extensions to the format of NDN messages or tables, lack a network-wide view, and often result in sub-optimal performance [59]. Last, none of the considered works includes a mechanism to recover the synchronization between consumer and producer after the handover.

2.2. SDN and related solutions for consumer mobility

The SDN paradigm introduces a number of technical strategies for optimizing control operations and answering, in real-time, to network demands. It enables the dynamic configuration of the network through a sharp separation between control plane and data plane [60]. In general, SDN manages mobility through reactive or proactive approaches. The former, investigated in [33–35, 61], supposes that the network attachment points notify the SDC every time a mobile user attaches or detaches from the network. This way, the SDC is able to update routing tables based on the knowledge of consumer mobility. The latter uses machine learning techniques to predict the position of mobile consumers and updates the network configuration accordingly. It achieves better performance in terms of delay and packet loss, but it may cause unnecessary data transmissions in case of wrong predictions [35].

Many works in the literature encompass the joint deployment of SDN and NDN with outstanding results [3–7, 62, 63]. In fact, the integration of SDN and ICN offers many advantages when compared against a “plain distributed ICN design”, including caching optimization [64, 65], routing optimization [3, 62], traffic engineering [66, 67], energy efficiency [68, 69], enhanced security [63, 70], and cooperative computing management [6]. At the same time, the solutions presented in [8–14] leverage SDN functionalities for mobility management in NDN networks: mobile users notify their attachment and detachment procedures to a centralized SDC and the SDC updates PIT and/or FIB tables in network nodes accordingly. While the contributions [11–14] focus on VANET scenarios (e.g. vehicle speed, information on the destination, and traffic conditions) to predict the availability of producers and consumers, those discussed in [8–10] refer to broader scenarios and consider producer mobility only. Nevertheless, they do not solve the problems related to the presence of stale disjoint links and the loss of synchronization caused by the handover. Furthermore, it is important to remark that SDN requires a flexible implementation of the control plane [71, 72]. In this context, the controller interacts with network elements through standardized APIs, namely Southbound Interface, and OpenFlow is the most popular solution supported by the Open Networking Foundation [60]. Despite OpenFlow is still considered the de facto standard, recent novel methodologies would encourage both research and development activities to move away from OpenFlow [36–39, 61, 73, 74]. Specifically, solutions like POF [36–38], P4/XDP [39, 61], and Control And Provisioning of Wireless Access Points (CAPWAP) [73, 74] have been introduced to improve the programmability of the network by increasing the expressiveness of the control plane, thus enabling a faster adoption of innovative protocols. But, all the reviewed contributions tackling mobility in NDN still consider the conventional OpenFlow protocol as a Southbound Interface and the possibility to adapt different approaches seems to be unexplored, yet.

2.3. Integration of MEC capabilities in ICN and/or SDN-based architectures

As a final remark, MEC is an emerging paradigm which brings computing power and caching to the edge of the network [75–78]. Network operators dispose MEC entities on the field to offer advanced services and support user mobility across multiple radio access technologies [75], while dynamically relocating context information of mobile users at the edge of the network [79], balancing network loads [80], predicting user mobility and optimizing handover [81].

Some recent works propose to use the MEC entity as a gateway, aggregating requests from mobile consumers and translating these requests to NDN communication primitives [30, 31]. Moreover, combining edge caching and Interest aggregation at the MEC level considerably reduces the load in the core network [32]. The current state of the art also presents several works encompassing the integration of MEC and SDN [40–45, 80]. The two paradigms offer mutual benefits to each other: SDN provides centralized control to MEC and offers common APIs for network programmability in heterogeneous technologies environment, while the deployment of MEC entities improves efficiency and reliability of SDN centralized control [77].

First attempts in the joint deployment of MEC, NDN, and SDN have been investigated in [25, 46, 68, 82, 83]. The proposals in [82], [46], and [25] evaluate the possibility to orchestrate named services in edge and fog domains by exploiting the centralized control of an SDC and the adaptive forwarding plane of NDN. Other works, such as [68] and [83], propose a framework for the optimal management of network resources to improve the energy efficiency and the hit ratio, respectively. While they present an interesting perspective on architecture integration and shed a light on the promising capabilities of the framework, the contributions in [25, 46, 68, 82, 83] do not propose any solution to the problems of stale paths and loss of synchronization. Therefore, the issues emerged from the studies presented in [24] and [26] still remain uncovered.

2.4. Final considerations

At the end of this Section, it is important to remark that this work does not propose "yet another approach" to manage seamless handover. Instead, it formulates a novel and effective protocol architecture (where the SDN controller covers a key role) that solves the issues affecting most of the strategies addressing data delivery to mobile consumers in NDN-based networks. Table 1 sketches the reviewed state of the art and compares the research contributions published so far with respect to the different technical aspects investigated in this work. It is clear that different important contributions in the current literature address consumer mobility and solve the service disruption issue. But, it also emerges that this work proposes a novel protocol architecture that solves, for the first time, mobility issues related to stale paths and loss of synchronization of real-time services. It also proposes, for the first time, an information-centric implementation of the SDN control plane, based on the usage of POF capabilities. Finally, differently from several analyses available in the current scientific literature, it analytically formulates and numerically evaluates the communication overhead in scenarios with one or more mobile consumers.

At the same time, it is important to note that the methodology formulated in this work can be properly adopted to improve the behavior of any other SDN-based protocol architecture willing to address consumer mobility in an NDN deployment, like [8–14].

3. The proposed protocol architecture

This work focuses on a multi-hop wireless mesh network (see Fig. 2). Many network attachment points are randomly located within a given geographical area and provide wireless connectivity to mobile consumers. According to the multi-access paradigm, the network may support heterogeneous communication technologies. But, at the higher layers of the protocol stack, all the nodes interact with each other through NDN, which transparently operates with respect to the technical details characterizing the underlying communication technologies. This is also valid for the control messages, that are exchanged within the multi-hop wireless mesh network (i.e., between the SDC and the routers) via NDN communication primitives. Each network attachment point hosts a MEC entity, whose goal is to assist mobile consumers during the data retrieving process while ensuring a seamless and transparent interface with the NDN network. On the other hand, SDN is integrated within the whole protocol architecture for dynamically configuring NDN network functionalities. In summary, the conceived protocol architecture implements Subscription, Data Exchange, Attachment, Inspection, and Re-synchronization procedures. All of them are implemented at the higher layers of the protocol stack. Therefore, they do not depend on the kind of communication technologies available at the wireless interface (in fact, heterogeneous technologies are transparently managed by NDN).

Table 1
Overview on the reviewed state of the art.

Works	NDN	SDN	Control plane implementation	MEC	Address consumer mobility	Solve consumer service disruption	Solve stale path	Solve loss of synchronization	Information-centric control plane	Single consumer overhead analysis	Multiple consumer overhead analysis
[73, 74]		X	CAPWAP								
[36–38]		X	POF								
[8, 64]	X	X									
[3–5, 7, 62, 63, 65–67, 69]	X	X	OpenFlow								
[75–78, 81]				X							
[30–32]	X			X							
[44]		X		X							
[17, 40, 41, 43, 71]		X	OpenFlow	X							
[70]	X	X			X						
[82]	X	X		X	X						
[25, 46, 68, 83]	X	X	OpenFlow	X	X						
[15, 19, 29, 49–51, 53–56]	X				X	X					
[11–14]	X	X			X	X					
[33–35]		X	OpenFlow		X	X					
[61]		X	P4		X	X					
[80]				X	X	X					
[9]	X	X								X	
[10]	X	X	OpenFlow							X	
[24, 58]	X				X					X	
[79]				X	X					X	
[48, 52, 57]	X				X	X				X	
[42, 45]		X	OpenFlow	X	X					X	
This work	X	X	POF	X	X	X	X	X	X	X	X

In line with the issues described in Section 2, this section will use the following key terminologies: *unuseful data* and *lost data*. The term "unuseful data" refers to the contents delivered, after the handover, across stale disjoint links due to stale forwarding information. The delivery of such contents generates a waste of bandwidth within stale disjoint links, thus hindering network performance. On the other hand, the term "lost data" describes the set of contents lost by the mobile consumer during the handover procedure.

The list of entities involved in each procedure, as well as the different exchanged messages, are reported in Table 2.

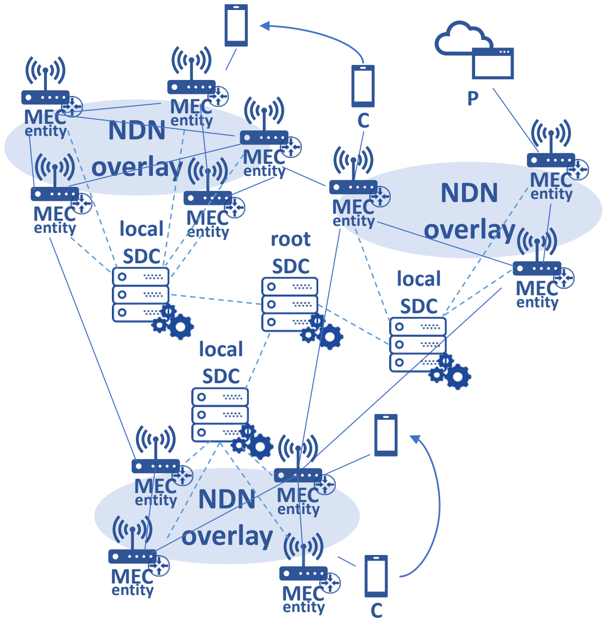

Figure 2: The reference network architecture.

3.1. The protocol architecture with a single SDN controller

For multi-hop wireless mesh networks made up of a limited number of network attachment points, it is conceivable to assume the presence of a single and centralized SDC. In this case, the conceived procedures are implemented as discussed below.

Table 2
An overview of procedures belonging to the conceived protocol architecture.

Procedure	Goal	Involved entities	Message name	Type of message	Average size
Subscription	Subscribe to a topic name	Consumer and MEC entity	Subscription Request	HTTP (POST)	S_R
Data Exchange	Retrieve desired data	MEC entities and Producer	Request	Interest packet	I_{INT}
			Response	Data packet	S_D
Attachment	Announce consumer attachment	SDC and MEC entities	Attachment Notification	Interest packet	I_{AN}
			Attachment Notification Confirmation	Data packet	D_{AN}
Inspection	Update PIT tables in network routers	SDC and MEC entities	Face Remove	Interest packet	I_{FR}
			Face Remove Confirmation	Data packet	D_{FR}
Re-synchronization	Announce the latest content generated	MEC entities and Producer	Re-sync Request	Interest packet	I_{RS}
			Re-sync Response	Data packet	D_{RS}

3.1.1. *Subscription procedure*

The interaction between the mobile consumer and the MEC entity follows the publish-subscribe mechanism. Once the consumer attaches to a new network attachment point, it delivers to the corresponding MEC entity a Subscription Request, which indicates the topic-name of its interest. The request is encoded with an HTTP POST message and establishes a high-level connection (a web socket, for instance) between the mobile consumer and the MEC entity. Then, the MEC entity executes the Attachment procedure (as discussed in Sec. 3.1.2), the Re-synchronization procedure (as discussed in Sec. 3.1.3), and the Data Exchange procedure (as described in Sec. 3.1.4). Differently from what happens in the rest of the network, mobile consumer and MEC entity do not communicate with each other by using information-centric primitives. Indeed, no Interest and Data packets are issued at this stage of the protocol. This makes the implementation of the end-user application independent from the protocol stack available beyond the network attachment point, i.e., within the multi-hop wireless mesh network.

3.1.2. *Attachment procedure*

The Attachment procedure is triggered by a MEC entity, upon the reception of a subscription request. Specifically, the MEC entity notifies the new location of the consumer and the topic name of its interest to the SDC. This is done by issuing the Attachment Notification message, encoded with an Interest packet having the content name set to $ndn://Attachment-Notification/[MEC-entity-name]/[topic-name]/[consumer-name]$. The SDC stores this information within a local database and releases a Data packet of confirmation, namely Attachment Notification Confirmation. Note that in case of handover, the SDC stores in its local database information related to the previous and the new network attachment points. Fig. 3 reports the message sequence chart describing the Attachment procedure.

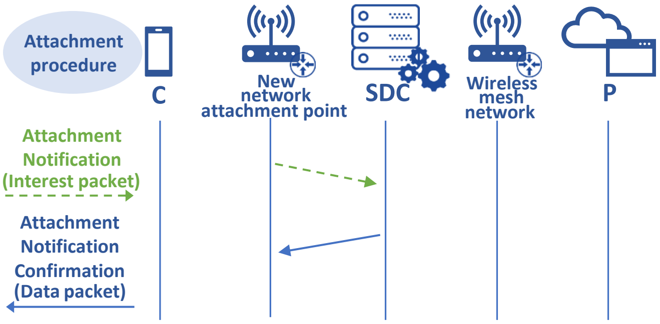

Figure 3: Messages exchanged during Attachment procedure.

3.1.3. Re-synchronization procedure

Before retrieving the contents requested by the mobile consumer, the new MEC entity must implement the Re-synchronization procedure, which represents a fundamental task for the following two reasons. First, the MEC entity does not know the ID of the latest content to request. Second, the interaction with the remote producer is useful to acquire the IDs of contents generated during the handover, especially after a long period of network detachment. As a result, the re-synchronization will ensure that the MEC entity will request up-to-date contents and, if necessary, retrieve lost data (i.e., contents which the mobile consumer was unable to receive during the handover). Indeed, the new MEC entity serving the consumer sends an Interest packet with the name set to $ndn : //[topic-name]/LAST/[timestamp]$. The producer answers with a Data packet containing the name of the latest content available for that topic-name. Fig. 4 shows the message sequence chart describing the Re-synchronization procedure.

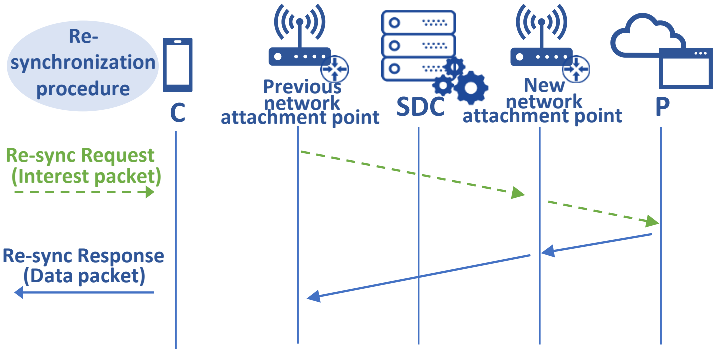

Figure 4: Messages exchanged during the Re-synchronization procedure.

3.1.4. Data Exchange procedure

In line with the NDN logic, the producer exposes real-time data under a specific topic-name. To simplify, a generic data can be identified with the content name $ndn : //[topic - name]/\#id$. During the Data Exchange procedure, the MEC entity starts retrieving new contents belonging to the subscribed topic by exploiting the conventional request-response communication scheme offered by NDN. Each request is implemented through an Interest packet, namely Request. Every time a new Response (implemented through a Data packet) is received, the MEC entity releases a new Request. Fig. 5 reports the message sequence chart describing the Data Exchange procedure.

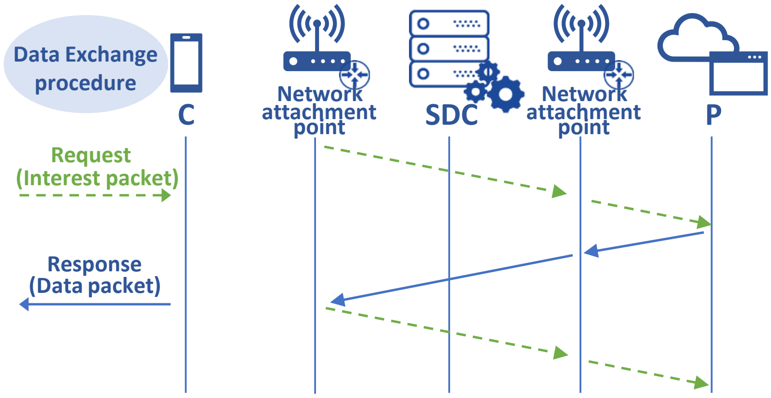

Figure 5: Messages exchanged during the Data Exchange procedure.

3.1.5. Inspection procedure

The Data Exchange procedure defines a new path between the mobile consumer and the producer. According o the NDN communication principles, the new request does not overwrite neither PIT nor FIB tables of the final part of the path. Instead, both communication paths (i.e., the one established between the new MEC entity and the remote producer after the handover and the other one established between the previous MEC entity and the same producer before the handover) remain active till the related PIT entries expire. To better manage mobility and real-time data delivery, the work presented in [24] suggests to set the lifetime of a PIT entry to the average amount of time between the generation of two consecutive contents belonging to the same topic name. Indeed, the stale disjoint path may remain active also after a long period of network detachment experienced by the mobile consumer in the case of non-overlapping cells. As a result, contents requested before the handover could be forwarded to the old location because of the wrong information stored in stale disjoint links. This inevitably brings to an unexpected waste of bandwidth. The SDC is now responsible for updating forwarding information stored within routers belonging to the stale disjoint path, i.e., by deleting the wrong PIT entries. This task is implemented through an iterative approach, namely Inspection procedure. Based on the way the path between the MEC entity serving the consumer and the remote producer is learned, two possible implementations are designed herein: Neighbor Inspection and Router Inspection. In both cases, the SDC starts investigating the previous network attachment point, whose details are stored within the local database (as anticipated in Section 3.1.2). Any control message is delivered across the network through information-centric primitives and processed following POF instructions. Fig. 6 shows the message sequence chart describing the generic Inspection procedure.

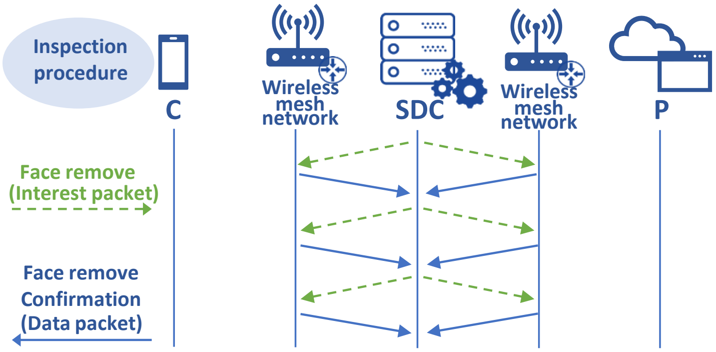

Figure 6: Messages exchanged during the Inspection procedure.

Neighbor Inspection) This procedure assumes that the SDC does not know a priori the path established between the MEC entity serving the consumer and the remote producer. In fact, even if the SDC knows the overall network topology (i.e., how and by which interface NDN routers are connected), it does not have any idea about the path followed by a specific Interest packet to reach the remote producer. As a consequence, it will learn that path by inspecting the network routers (first) and it will remove stale forwarding information from the routers of the discovered path (then). The inspection starts from the router corresponding to the previous consumer location (i.e., the node where the consumer was attached before the handover) and potentially ends when the router which the producer is attached to is reached. At every round, the SDC sends a Face Remove message to the investigated router. This message represents an Interest packet with the content name set to $ndn : //Face - Remove/[node - name]/[topic - name]/[face]$. The content name reports the topic-name of interest for the consumer and the face that should have received the request (which is set by the SDC at every step of the procedure, according to the known network topology). The router that receives the Face Remove message compares the topic-name of pending requests with those stored in the entries of its PIT table. PIT entries that match, at the same time, the topic-name of pending requests and the face indicated by the SDC are firstly selected. Then, those containing only the face indicated by the SDC are deleted. The presence of more than one face in the other PIT entries demonstrates that the considered contents have been requested by other consumers from other paths. In this case, the router just erases the face indicated by the SDC from these entries. In the end, the router sends back to the SDC a Data packet, namely Face Remove Confirmation, notifying the list of content names effectively deleted from the PIT table. This way, the SDC learns which router had stale information. Then, the SDC contacts all the neighbors of the router which answered with a non-empty packet at the previous round. The SDC is able to accomplish this task because it knows the overall network topology. Indeed, the SDC sends the Face Remove message to all the identified neighbors and indicates, through the content name stored within the Interest packet, the face connecting the investigated router with the previous one and the topic-name of pending requests. The neighbors implement the same tasks discussed before and notify to the SDC of the list of deleted entries. The SDC iterates the protocol until it receives empty Face Remove Confirmation messages only, which implies that the SDC removed all the stale information across the stale disjoint path.

A concrete example is depicted in Fig. 7, showing a mobile consumer moving from R_1 to R_6. The Inspection procedure starts after the Re-synchronization procedure, when the mobile consumer is attached to R_6. The local SDC sends a Face Remove message to R_1, which sent the Attachment Notification message. The Face Remove message stores the name of the requested content and the interface which connects R_1 to the mobile consumer. R_1 compares the information received within the Face Remove message with its PIT table and answers to the local SDC with a Face Remove Confirmation message, storing the content name of the requested content and the interface related to the deleted PIT entry. Then, the local SDC sends a Face Remove message to the 1-hop neighbors of R_1. The message stores the content name related to the deleted PIT entry and the face which connects the inspected neighbor to R_1. Among all the inspected neighbors, only R_2 has PIT entries matching both the content name and the face, acknowledging that the content request came from R_1. Then, R_2 answers with a Face Remove Confirmation message to the local SDC. Finally, the SDC sends a Face Remove message to the 1-hop neighbors of R_2. Again, the Face Remove message carries the content name of the requested content and the face which connects the inspected neighbor to R_2. This time, R_3 finds PIT entries that also include other faces (i.e., the face that connects R_3 to R_6) and answers to the SDC with an empty Face Remove Confirmation message. The local SDC stops the implementation of the Inspection procedure, as it received only empty Face Remove Confirmation messages. Definitively, all stale information has been removed.

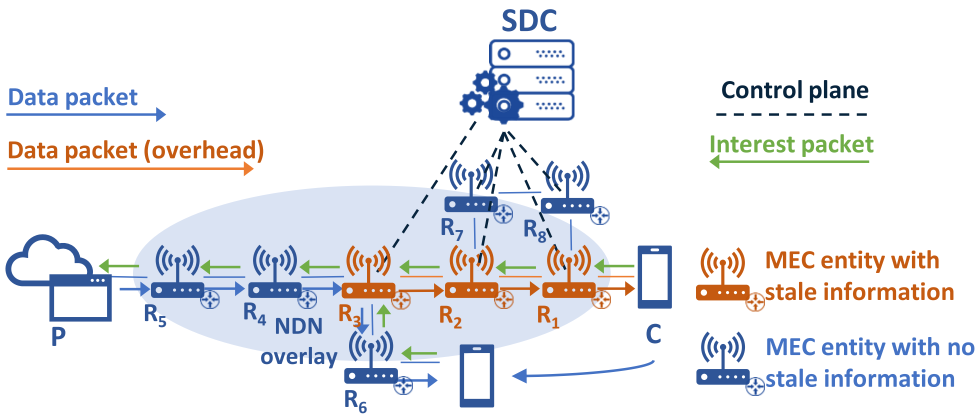

Figure 7: An example showing the Inspection procedure.

Router Inspection) The Router Inspection approach assumes that the SDC knows the path established between the MEC entity serving the consumer and the remote producer. Face Remove messages are not sent to all the neighbors anymore. Instead, the SDC iteratively inspects routers of the stale disjoint path, which may contain stale information. Similarly to the Neighbor Inspection approach, it sends a Face Remove message (i.e., an Interest packet whose content name is set to $ndn : //Face - Remove/[node - name]/[topic - name]/[face]$) to the inspected router, asking it to compare the information stored in the content names with its PIT entries. Then, the router sends back a Face Remove Confirmation message announcing content names for deleted entries. Accordingly, the SDC stops when it receives an empty Face Remove Confirmation message, meaning that it removed all stale information from the stale disjoint path.

Fig. 7 can still be used to formulate a concrete example. When the mobile consumer attaches to R_6, after the Re-synchronization procedure, the local SDC sends a Face Remove message to R_1. The Face Remove message stores the content name of the requested content and the interface which connected R_1 to the mobile consumer. R_1 matches the received information with its PIT table and answer to the local SDC with a Face Remove Confirmation message, storing the content name of the requested content and the interface related to the deleted PIT entry. Then, the local SDC inspects the next router belonging to the path established between the MEC entity serving the consumer and the producer (i.e., R_2). The message stores the content name related to the deleted PIT entry and the face which connects R_2 to R_1. Then, R_2 answers with a Face Remove Confirmation message to the local SDC. Finally, the SDC sends a Face Remove message to R_3, that answers with an empty Face Remove Confirmation message. The local SDC stops the implementation of the Inspection procedure, as all stale information have been removed.

3.2. The protocol architecture with multiple SDN controllers

As expected, scalability grows in importance as the workload on the SDC increases. Thus, the execution of several complex operations on densely populated networks requires sophisticated solutions that inevitably counteract performance degradation. In large-scale deployments, the proposed protocol architecture could leverage multiple SDN controllers, organized according to a hierarchical model [72]: a root controller holds network-wide information and coordinates local SDN controllers; each local SDC manages a specific set of network attachment points belonging to its domain and holds information on attached consumers. In the case the stale disjoint path passes through more domains, the conceived protocol architecture must be modified in both the Attachment and Inspection procedures.

3.2.1. *Revised Attachment procedure in case of multiple SDN controllers*

The Attachment procedure starts when the mobile consumer attaches to a new network attachment point. The reference MEC entity notifies the local SDC with an Attachment Notification message. The local SDC apprehends that the consumer moved from another domain because it does not contain any information in its local database. As a consequence, the new local SDC polls the root controller by announcing the handover event. In turn, the root controller polls the local controllers notifying the name of the mobile consumer. Then, the local SDC which previously held information on the consumer answers to the root controller and starts the Inspection procedure.

3.2.2. *Revised Inspection procedure in case of multiple SDN controllers*

The local SDC that previously held information on the consumer starts the inspection from the router hosting the MEC entity where the consumer was attached before the handover. The procedure follows the same scheme detailed in Sec. 3.1 until a router belonging to a different domain is reached. In this case, the controller that started the Inspection procedure sends the name of the last router inspected to the root controller. The latter notifies the reference local controller about the name of the router it should start inspecting from. Then, the procedure continues as detailed in Sec. 3.1 until all stale information is removed.

4. Modeling the communication overhead

According to the scientific contribution published in [24], consumer mobility in an NDN network inevitably brings to a communication overhead due to the exchange of control messages and the dissemination of Data packets across the links of the stale disjoint path. Even though SDN is introduced for reducing the waste of bandwidth due to the dissemination of Data packets across these links, new control messages need to be exchanged among MEC entities, routers, and the SDCs. Indeed, the analysis of the communication overhead initially provided in [24] must be revised. The goal of this Section is to formulate analytical models able to quantify the communication overhead produced by the conceived protocol architecture in the presence of one or more mobile consumers. A summary of the main symbols adopted below is presented in Table 3.

In line with [24], the communication overhead is formally defined as the total amount of bits related to messages on both the control plane and the data plane, exchanged at the application layer on the links of the multi-hop wireless mesh network in a unit of time. It is independent of the communication technology implemented at the lower layer of the protocol stack, which may induce packet fragmentation at the link level. As expected, Subscription, Attachment, Re-synchronization, Data Exchange, and Inspection procedures provide different contributions to the communication overhead due to control messages. Unuseful data, instead, still refers to the amount of Data packets delivered through the links of the stale disjoint path before that the Inspection procedure deleted all the wrong forwarding information in PIT entries. Indeed, it is important to remark that the conducted analysis only considers the signaling, and the corresponding overhead, related to the management of consumer mobility, as any other control communication remains unchanged and does not influence the KPIs investigated in Sec. 5. Also, the analysis considers the scenario with a single SDC, but it can be simply extended for deployments having multiple controllers. Let $E[\Delta t_c]$ be the average cell residence time, that is the amount of time the consumer is connected to a specific MEC entity before attaching to a new one because of its mobility. Given the average cell radius, r, and the average consumer speed, v, the average cell residence time is set to $E[\Delta t_c] = \frac{\pi r}{2v}$ as in [84]. Moreover, d represents the average shortest path length between any

Table 3
List of model symbols.

Symbol	Description
Δt_c	Cell residence time of the consumer
L	Number of mobile consumers interested in the same contents
v	Average consumer speed
r	Average cell coverage radius
τ	Round Trip Time of the Network
δ	Processing time
T_D	Interarrival time
k	Average number of neighbors per router
A	Average number of routers on the stale disjoint path
d	Average shortest path between two nodes in the network
D	Average number of active links in the network
S_R	Packet size for Subscription Request
I_{INT}	Packet size for Request
S_D	Packet size for Response
I_{AN}	Packet size for Attachment Notification
D_{AN}	Packet size for Attachment Notification Confirmation
I_{FR}	Packet size for Face Remove
D_{FR}	Packet size for Face Remove Confirmation
I_{RS}	Packet size for Re-sync Request
D_{RS}	Packet size for Re-sync Response

node pair. At the application layer, the producer generates data packets with an average size equal to S_D according to the Poisson law with parameter $\frac{1}{T_D}$. Therefore, the average time interval between the generation of two consecutive content is equal to T_D.

The average cell residence time is used as the reference observation time for calculating the communication overhead. Moreover, let O_{SUB}, O_{INT}, O_{AT}, O_{RS}, O_{IN}, and O_{DATA} be the contributions to the communication overhead due to the subscription request sent by the mobile consumer to the reference MEC instance, the set of Interest packets issued by the MEC entity to retrieve contents during the Data Exchange procedure, control messages exchanged during the Attachment procedure, messages to restore the synchronization exchanged during the Re-synchronization procedure, control messages exchanged during the Inspection procedure, and unuseful Data, respectively. Definitively, the average communication overhead can be formally defined as:

$$\bar{O} \quad = \quad \frac{E[O_{SUB} + O_{INT} + O_{AT} + O_{RS} + O_{IN} + O_{DATA}]}{E[\Delta t_c]}, \tag{1}$$

where $E[\cdot]$ refers to the expectation operator.

4.1. Communication overhead expected in scenarios with a single consumer

With reference to a scenario with a single consumer, Theorem 1 and Theorem 2 formulate the communication overhead due to the proposed protocol architecture when the Neighbor Inspection and Router Inspection algorithms are implemented, respectively.

Theorem 1. *Let d, Δt_c, T_D, k, A, and τ be the average shortest path length, the average cell residence time of the mobile consumer, the time interval between the production of two consecutive contents, the average number of 1-hop neighbors per router, the average number of routers on the stale disjoint path, and the round trip time of the network. Considering that the generation of packets follows a Poisson law with parameter $\frac{1}{T_D}$, the average communication overhead registered when the Neighbor Inspection algorithm is implemented is equal to:*

$$\bar{O}\Big|_{N.\,Insp} \quad = \quad \frac{S_R}{\Delta t_c} +$$

$$\begin{aligned}
&+ \quad \frac{dI_{INT}}{\Delta t_c}\left(1+\frac{\Delta t_c}{T_D}\right)+\\
&+ \quad \frac{d}{\Delta t_c}(I_{AN}+D_{AN})+\\
&+ \quad \frac{d}{\Delta t_c}(I_{RS}+D_{RS})+\\
&+ \quad \frac{d}{\Delta t_c}(I_{FR}+D_{FR})((A-1)(k-1)+2)+\\
&+ \quad \frac{S_D}{\Delta t_c}\left(A+e^{-\frac{\tau}{T_D}}-\frac{1-e^{-(A+1)\frac{\tau}{T_D}}}{1-e^{-\frac{\tau}{T_D}}}\right),
\end{aligned} \tag{2}$$

where S_R, I_{INT}, S_D, I_{AN}, D_{AN}, I_{FR}, D_{FR}, I_{RS}, and D_{RS} are the average size of Subscription Request, Request, Response, Attachment Notification, Attachment Notification Confirmation, Face Remove, Face Remove Confirmation, Re-sync Request, and Re-sync Response messages, respectively.

Proof. The consumer sends a Subscription Request message to the MEC entity hosted by its reference network attachment point. The related contribution to the communication overhead is simply equal to:

$$E[O_{SUB}] \;=\; E\left[S_R\right] = S_R. \tag{3}$$

Then, during the Data Exchange procedure, the related MEC entity starts pulling the contents to retrieve by sending an Interest packet. The consumer releases a new Interest packet every time a new Data packet is received. This happens every T_D, till the end of the average cell residence time $E[\Delta t_c] = \frac{\pi r}{2v}$. Let I_{INT} and $d_{M\to P}$ be the size of the Interest packet and the distance between the MEC entity implementing the Data Exchange procedure and the router which the producer is attached to, respectively. Then, as already demonstrated in [24], the average communication overhead due to the data exchange, $E[O_{INT}]$, is equal to:

$$E[O_{INT}] \;=\; E\left[d_{M\to P}I_{INT}\left(1+\frac{\Delta t_c}{T_D}\right)\right] = E\left[d_{M\to P}\right]I_{INT}\left(1+\frac{\Delta t_c}{T_D}\right) = dI_{INT}\left(1+\frac{\Delta t_c}{T_D}\right). \tag{4}$$

Note that T_D and I_{INT} have been introduced as average values. Therefore they are considered as constant terms by the expectation operator $E[\cdot]$. Differently, $E[d_{M\to P}] = d$.

During the Attachment procedure, two control messages are exchanged: the Attachment Notification message (with a size equal to I_{AN}) is sent by the MEC entity that started the Attachment procedure to the remote SDC; the Attachment Notification Confirmation message (with a size equal to D_{AN}) is sent by the SDC to acknowledge the new position of the consumer. Note that $d_{M'\to C}$ represent the distance between the MEC entity serving the consumer after the handover and the SDC. Therefore, by assuming $E[d_{M'\to C}] = d$, the average communication overhead due to the Attachment procedure is equal to:

$$E[O_{AT}] \;=\; E[d_{M'\to C}(I_{AN}+D_{AN})] = E[d_{M'\to C}](I_{AN}+D_{AN}) = d(I_{AN}+D_{AN}). \tag{5}$$

The execution of Re-synchronization procedure envisages the exchange of Re-sync Request and Re-sync Response messages. Its contribution to the communication overhead is $O_{RS} = (I_{RS}+D_{RS})d_{M'\to P}$. Considering average shortest path length $E[d_{M'\to P}] = d$ and the size of the aforementioned messages (I_{RS} and D_{RS}), the average communication overhead due to the Re-synchronization procedure is equal to:

$$E[O_{RS}] \;=\; E\left[d_{M'\to P}(I_{RS}+D_{RS})\right] = E\left[d_{M'\to P}\right](I_{RS}+D_{RS}) = d(I_{RS}+D_{RS}). \tag{6}$$

A more complex discussion should be done for the Neighbor Inspection procedure. Let r_i be the $i-th$ router belonging to the stale disjoint path. r_1, for instance, represents the router hosting the MEC entity where the consumer was previously attached. Let n_{ij} be the $j-th$ neighbor of r_i. To simplify the notation, it is assumed that the average number of routers belonging to the stale disjoint path is equal to A. Moreover, I_{FR} and D_{FR} represent the size of Face Remove and Face Remove Confirmation messages, respectively. The distance between r_i and the SDC is denoted with $d_{r_i \to C}$. Similarly, the distance between the node n_{ij} and the SDC is denoted with $d_{n_{ij} \to C}$. The Inspection procedure starts investigating the PIT tables of the first node of the path and its neighbors. The resulting communication overhead is equal to $d_{M \to C}(I_{FR}+D_{FR})+\sum_{j=1}^{k} d_{n_{1j} \to C}(I_{FR}+D_{FR})$. Starting from r_2, only k-1 neighbors of the considered router of the disjoint path are investigated. In fact, the current node and the previous router of the path (i.e., a neighbor of the current node) have been already investigated one step before. Thus, each new interaction of the protocol produces a contribution to the communication overhead equal to $\sum_{j=1}^{k-1} d_{n_{ij} \to C}(I_{FR} + D_{FR})$. Without loss of generality, it is assumed that the Inspection procedure investigates all the routers of the stale disjoint path. The SDC must inspect every single router on the stale disjoint path to remove stale information and avoid removing up-to-date forwarding information from aggregated PIT entries. In fact, even if the SDC knows the router where the old and the new paths join, removing the face related to the old requests of the mobile consumer could hinder the requests of other consumers that are aggregated on the other routers of the stale disjoint path. In this case, the contribution to the communication overhead due to the Inspection procedure is equal to:

$$\begin{aligned}
E[O_{IN}]\Big|_{\text{N. Insp}} &= E\left[d_{M \to C}(I_{FR}+D_{FR}) + \sum_{j=1}^{k} d_{n_{1j} \to C}(I_{FR}+D_{FR}) + \sum_{i=2}^{A-1}\sum_{j=1}^{k-1} d_{n_{ij} \to C}(I_{FR}+D_{FR})\right] = \\
&= (I_{FR}+D_{FR})E\left[d_{M \to C}\right] + (I_{FR}+D_{FR})E\left[\sum_{j=1}^{k} d_{n_{1j} \to C}\right] + (I_{FR}+D_{FR})E\left[\sum_{i=2}^{A-1}\sum_{j=1}^{k-1} d_{n_{ij} \to C}\right] = \\
&= (I_{FR}+D_{FR})d + (I_{FR}+D_{FR})kd + (I_{FR}+D_{FR})(A-2)(k-1)d = \\
&= d(I_{FR}+D_{FR})(1+k+(A-2)(k-1)) = d(I_{FR}+D_{FR})((A-1)(k-1)+2).
\end{aligned} \tag{7}$$

Although the goal of the SDC is to delete stale information of PIT entries, Data packets may still be forwarded across the links belonging to the stale disjoint path before the end of the Inspection procedure. Let τ and δ be the round trip time and the time needed to process the Face Remove message. Since $\delta << \tau$, it is assumed that δ is negligible with respect to τ. The stale disjoint path is made up by A routers and the stale forwarding information of the $i-th$ router of the stale disjoint path can be deleted after $i\tau$ from the beginning of the cell residence time. Therefore, the contribution to the communication overhead due to the delivery of unuseful data is equal to $S_D(A-1)$ if a new content is generated within the time interval 2τ from the begin of the cell residence time (with probability $P(0 \le t < 2\tau)$), $S_D(A-2)$ if a new content is generated in the interval between 2τ and 3τ (with probability $P(2\tau \le t < 3\tau)$), from the beginning of the cell residence time, and so on. No unuseful Data packets are exchanged if the new content is generated after $A\tau$ from the beginning of the cell residence time. Considering that the contents are generated according to the Poisson law with parameter $\frac{1}{T_D}$, it holds that $P(0 \le t < 2\tau) = P(0 \le t < \tau) + P(\tau \le t < 2\tau) = 1 - e^{-\frac{2\tau}{T_D}}$ and $P(i\tau \le t < (i+1)\tau) = (1 - e^{-\frac{(i+1)\tau}{T_D}}) - (1 - e^{-\frac{i\tau}{T_D}})$. Therefore, $E[O_{DATA}]$ can be expressed as:

$$\begin{aligned}
E[O_{DATA}] &= S_D\left(P(0 \le t < \tau)(A-1) + \sum_{i=1}^{A-1} P(i\tau \le t < (i+1)\tau)(A-i)\right) = \\
&= S_D\left((1 - e^{-\frac{\tau}{T_D}})(A-1) + \sum_{i=1}^{A-1}((1-e^{-(i+1)\frac{\tau}{T_D}})-(1-e^{-i\frac{\tau}{T_D}}))(A-i)\right) = \\
&= S_D\left((1 - e^{-\frac{\tau}{T_D}})(A-1) + \sum_{i=1}^{A-1} e^{-i\frac{\tau}{T_D}}(1-e^{-\frac{\tau}{T_D}})(A-i)\right) =
\end{aligned} \tag{8}$$

$$= S_D\left((1 - e^{-\frac{\tau}{T_D}})(A-1) + (1-e^{-\frac{\tau}{T_D}})A\sum_{i=1}^{A-1} e^{-i\frac{\tau}{T_D}} - (1 - e^{-\frac{\tau}{T_D}})\sum_{i=1}^{A-1} ie^{-i\frac{\tau}{T_D}} \right)=$$

$$= S_D\left(A + e^{-\frac{\tau}{T_D}} - \frac{1 - e^{-(A+1)\frac{\tau}{T_D}}}{1 - e^{-\frac{\tau}{T_D}}} \right).$$

Now, by substituting (3), (4), (5), (6), (7), and (8) in (1), it is possible to prove the theorem.

□

Theorem 2. *Let d, Δt_c, T_D, A, and τ be the average shortest path length, the average cell residence time of the mobile consumer, the time interval between the production of two consecutive contents, the average number of routers on the stale disjoint path, and the round trip time of the network. Considering that the generation of packets follows a Poisson law with parameter $\frac{1}{T_D}$, the average communication overhead registered when the Router Inspection algorithm is implemented is equal to:*

$$\begin{aligned}
\bar{O}\Big|_{\text{R. Insp}} &= \frac{S_R}{\Delta t_c} + \\
&+ \frac{dI_{INT}}{\Delta t_c}\left(1 + \frac{\Delta t_c}{T_D}\right) + \\
&+ \frac{d}{\Delta t_c}(I_{AN} + D_{AN}) + \\
&+ \frac{d}{\Delta t_c}(I_{RS} + D_{RS}) + \\
&+ \frac{d}{\Delta t_c}(I_{FR} + D_{FR})(A-1) + \\
&+ \frac{S_D}{\Delta t_c}\left(A + e^{-\frac{\tau}{T_D}} - \frac{1 - e^{-(A+1)\frac{\tau}{T_D}}}{1 - e^{-\frac{\tau}{T_D}}} \right),
\end{aligned} \tag{9}$$

where I_{INT}, S_D, I_{AN}, D_{AN}, I_{FR}, D_{FR}, I_{RS}, and D_{RS} are the average size of Request, Response, Attachment Notification, Attachment Notification Confirmation, Face Remove, Face Remove Confirmation, Re-sync Request, and Re-sync Response messages, respectively.

Proof. The contribution to the communication overhead due to the Data Exchange, Attachment, and Re-synchronization procedures remains the same also in this case. Differently, the overhead due to the Inspection procedure must be revised. When the Router Inspection algorithm is implemented, only the routers of the stale disjoint path are investigated. The contribution to the communication overhead is equal to $d_{M\to C}(I_{FR} + D_{FR})$ (for the first node) and $d_{r_i\to C}(I_{FR} + D_{FR})$ (for the other ones). Therefore:

$$\begin{aligned}
E[O_{IN}]\Big|_{\text{R. Insp}} &= E\left[d_{M\to C}(I_{FR}+D_{FR}) + \sum_{j=2}^{A-1} d_{r_j\to C}(I_{FR} + D_{FR})\right]=(I_{FR} + D_{FR})d + (I_{FR} + D_{FR})E\left[\sum_{j=2}^{A-1} d_{r_j\to C}\right]= \\
&= (I_{FR} + D_{FR})d + (I_{FR} + D_{FR})(A-2)d = d(I_{FR} + D_{FR})(A-1).
\end{aligned} \tag{10}$$

Now, by substituting (3), (4), (5), (6), (8), and (10) in (1), the theorem is proved. □

4.2. Communication overhead expected in scenarios with multiple consumers

With reference to a scenario with multiple consumers, Theorem 3 and Theorem 4 formulate the communication overhead due to the proposed protocol when the Neighbor Inspection and the Router Inspection algorithms are implemented, in the multiple consumer scenario, respectively.

Theorem 3. *Let Δt_c, T_D, d, D, A, and L be the average cell residence time, the time interval between the production of two consecutive contents, the average shortest path length between any two nodes, the average number of active links in the network during the cell residence time, the average number of stale disjoint links, and the number of consumers requesting the same contents. Considering that the generation of packets follows a Poisson law with parameter $\frac{1}{T_D}$, the average communication overhead registered when the Neighbor Inspection algorithm is implemented is equal to:*

$$\begin{aligned}\bar{O}\Big|_{N.\ Insp} &= \frac{L}{\Delta t_c} S_R + \\ &+ \frac{L}{\Delta t_c}\left(d I_{INT} + \frac{\Delta t_c}{L T_D} D I_{INT}\right) + \\ &+ \frac{dL}{\Delta t_c}(I_{AN} + D_{AN}) + \\ &+ \frac{dL}{\Delta t_c}(I_{RS} + D_{RS}) + \\ &+ \frac{dL}{\Delta t_c}(I_{FR} + D_{FR})((A-1)(k-1)+2) + \\ &+ \frac{L}{\Delta t_c} S_D \left(A + e^{-\frac{\tau}{T_D}} - \frac{1 - e^{-(A+1)\frac{\tau}{T_D}}}{1 - e^{-\frac{\tau}{T_D}}}\right),\end{aligned} \tag{11}$$

where I_{INT}, S_D, I_{AN}, D_{AN}, I_{FR}, D_{FR}, I_{RS}, and D_{RS} are the average size of Request, Response, Attachment Notification, Attachment Notification Confirmation, Face Remove, Face Remove Confirmation, Re-sync Request, and Re-sync Response messages, respectively.

Proof. The contribution to the communication overhead due to the Subscription, Attachment, Re-synchronization, and Inspection procedures remains the same as for the single consumer scenario. Differently, the overhead due to the Data exchange procedure has to be revised, starting from the re-definition of the average cell residence time. Given that L consumers are moving independently in an area covered by network attachment points, the cell residence time of the $i-th$ consumer can be modeled as an exponential random variable with parameter λ_i [84]. For the sake of simplicity, it is also assumed that a single user can change network attachment point at a time and all mobile consumers have the same parameter $\lambda_i = \lambda$. Let $P(\Delta t_{c,i} \geq T)$ be the probability that the residence time of the $i-th$ user $\Delta t_{c,i}$ is greater or equal than T, describing the probability that the $i-th$ consumer does not change its network attachment point during the time interval T. Then, the probability that L users do not change network attachment point during the time interval T, $P_L(\Delta t_L \geq T)$, is equal to:

$$P_L(\Delta t_L \geq T) = \prod_{i=1}^{L} P(\Delta t_{c,i} \geq T) = \prod_{i=1}^{L} e^{-\lambda T} = e^{-L\lambda T}. \tag{12}$$

The average cell residence time of the consumers in the network, i.e., the time between two consecutive handovers registered within the whole network, is equal to:

$$E[\Delta t_L] = \frac{1}{L\lambda} = \frac{\Delta t_c}{L}, \tag{13}$$

where Δt_c is the average cell residence time of a single consumer.

During the Data Exchange procedure, the related MEC entity starts pulling the contents to retrieve by sending an Interest packet, which aggregates with other requests from users interested in the same content. The consumer releases a new Interest packet every time a new Data packet is received. This happens every T_D, till the end of the average cell residence time $E[\Delta t_c] = \frac{\pi r}{2 v L}$. Let I_{INT} and $d_{M \to P}$ be the size of the Interest packet and the distance between the MEC entity implementing the Data Exchange procedure and the router which the producer is attached to, respectively. Also, let D be the number of active links during the cell residence time (i.e, the links over which Interest and Data packets of all consumers interested in the same contents are exchanged on). Indeed, the average communication overhead due to the data exchange, $E[O_{INT}]$, is equal to:

$$E[O_{INT}]=dI_{INT}+\frac{\Delta t_c}{LT_D}DI_{INT} \tag{14}$$

By substituting (3), (5), (6), (7), (8), (13), and (14) in (1), the theorem is proved.

□

Theorem 4. *Let Δt_c, T_D, d, D, A, and L be the average cell residence time, the time interval between the production of two consecutive contents, the average shortest path length between any two nodes, the average number of active links in the network during the cell residence time, the average number of stale disjoint links, and the number of consumers requesting the same contents. Considering that the generation of packets follows a Poisson law with parameter $\frac{1}{T_D}$, the average communication overhead registered when the Router Inspection algorithm is implemented is equal to:*

$$\begin{aligned}
\bar{O}\Big|_{R.\ Insp} \quad = \quad & \frac{S_R}{\Delta t_c}+ \\
+ \quad & \frac{L}{\Delta t_c}\left(dI_{INT}+\frac{\Delta t_c}{LT_D}DI_{INT}\right)+ \\
+ \quad & \frac{dL}{\Delta t_c}(I_{AN}+D_{AN})+ \\
+ \quad & \frac{dL}{\Delta t_c}(I_{RS}+D_{RS})+ \\
+ \quad & \frac{dL}{\Delta t_c}(I_{FR}+D_{FR})(A-1)+ \\
+ \quad & \frac{L}{\Delta t_c}S_D\left(A+e^{-\frac{\tau}{T_D}}-\frac{1-e^{-(A+1)\frac{\tau}{T_D}}}{1-e^{-\frac{\tau}{T_D}}}\right),
\end{aligned} \tag{15}$$

where I_{INT}, S_D, I_{AN}, D_{AN}, I_{FR}, D_{FR}, I_{RS}, and D_{RS} are the average size of Request, Response, Attachment Notification, Attachment Notification Confirmation, Face Remove, Face Remove Confirmation, Re-sync Request, and Re-sync Response messages, respectively.

Proof. The contribution to the communication overhead due to the Subscription, Data Exchange and Re-synchronization procedures remains the same as for the scenario with multiple consumers. Differently, the overhead due to the Attachment and Inspection procedure must be revised as already done in Theorem 2. Therefore, by substituting (3), (5), (6), (8), (10), (13), (14) in (1), the theorem is proved. □

5. Numerical Results

The communication overhead generated by the conceived protocol architecture is herein numerically evaluated in scenarios with different topology, mobility, and application settings, as well as various numbers of mobile consumers. The numerical evaluation also includes a comparison with the communication overhead generated by the behavior of several reference pull-based approaches, like those in [8–14, 30, 31], that do not solve the problems related to stale paths and loss of synchronization. This would provide a clear idea about the ability of the proposed approach to offer evident benefits in a very large set of (non-simplistic) assumptions. MATLAB scripts are used to simulate consumer mobility and obtain numerical results[1]. The conducted numerical study considers real topologies (and, in turn, real communication paths and stale disjoint paths) generated through a well-known simulator, capable of iteratively generating scale-free topologies, namely Representative Internet Topology gEnerator (BRITE) [85]. At the same time, results have been obtained by considering real application models (from the state of the art [17–19, 22, 23] and 3GPP standards [20]). Regarding the size of the messages (including Interest and Data packets), the 0.1.1 version of the NDN packet format specification, as described in [86], is taken into account. In this way, the considerations and obtained results become comparable with those reported in other recent works published in scientific literature [24, 47, 70, 87, 88]. The list of investigated KPIs are defined below:

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[1] The code is available on GitHub at https://github.com/telematics-lab/SDN-MEC-ICN-consumer-mobility.

- **Average communication overhead on the data plane**. According to the discussion presented in both Sec. 3 and Sec. 4, it represents the amount of unuseful data delivered across stale disjoint links. The proposed study compares the behavior of the conceived protocol architecture with respect to the pure NDN deployment where consumer mobility is simply addressed through the baseline pull-based strategy (as analytically formulated in [24]).

- **Average communication overhead on the control plane**. It quantifies the impact of control messages exchanged within the network, generated by the Attachment and the Inspection procedures. First, the overhead generated with the implementation of Neighbor and Router Inspection procedures is compared by assuming a control plane fully implemented through information-centric primitives (which represents the proposed solution that makes use of POF instructions to deliver control messages). To provide further insight, the discussed investigation also considers the average communication overhead on the control plane achieved when both the Inspection procedures are implemented through the OpenFlow protocol. Of course, POF-based and OpenFlow-based implementations of the Inspection procedures follow the same logic. The contribution to the communication overhead introduced by the implementation based on the conventional OpenFlow protocol of the Inspection procedure is partially revised as summarized in what follows. The Attachment procedure comprises a Port Status message, to notify the attachment, and a Packet_IN message, to notify the SDC about the topic-name of interest. The Inspection procedure considers a Modify Flow Entry message to remove the face related to the consumer from aggregated PIT entries, a Modify Flow Entry message to delete PIT entries related to the consumer only, and a Flow Removed message to notify the SDC about the deleted entries and enable the Interest path discovery.

- **Overhead reduction**. It represents the difference, expressed in percentage, between the overhead generated by the baseline pull-based approach implemented in a pure NDN approach and the overhead generated by the proposed protocol architecture. The study considers both the POF-based and the OpenFlow-based implementations for the control plane, as well as the Router Inspection and Neighbor Inspection procedures. The overhead reduction is calculated as:

  $$O_{reduction} = \frac{\bar{O}\Big|_{\text{Baseline NDN}} - \bar{O}}{\bar{O}\Big|_{\text{Baseline NDN}}} 100,$$

  where $\bar{O}\Big|_{\text{Baseline NDN}}$ is equal to $\frac{1}{\Delta t_c}\left(S_R + \left(1 + \frac{\Delta t_c}{T_D}\right) d I_{INT} + (A-1) S_D\right)$, as presented in [24].

  In scenarios with multiple consumers, the overhead generated by the baseline pull-based approach implemented in a pure NDN approach, $\bar{O}\Big|_{\text{Baseline NDN}}$, is partially revised by taking into account the considerations illustrated in Th. 3. In this case, $\bar{O}\Big|_{\text{Baseline NDN}}$ is equal to $\frac{L}{\Delta t_c}\left(S_R + \left(d + \frac{D\Delta t_c}{L T_D}\right) I_{INT} + (A-1) S_D\right)$.

- **Bandwidth savings**. It quantifies the overall bandwidth savings achieved when considering any kind of messages exchanged during the service provisioning. Indeed, during the cell residence time, the producer generates an average number of Data packets equal to $\frac{E[\Delta t_c]}{T_D}$. Given the size of a Data packet S_D, the average bandwidth consumed for actually transmitting new versions of requested contents during the average cell residence time, and for all the links of the path established between the producer and the MEC entity serving the mobile consumer, is equal to: $E\left[(\frac{E[\Delta t_c]}{T_D} S_D d_{M\to P})/E[\Delta t_c]\right] = \frac{d S_D}{T_D}$. Therefore, the overall bandwidth savings, $B_{savings}$ in a scenario with a single consumer is calculated as:

  $$B_{savings} = \frac{(\bar{O}\Big|_{\text{Baseline NDN}} + \frac{dS_D}{T_D}) - (\bar{O} + \frac{dS_D}{T_D})}{\bar{O}\Big|_{\text{Baseline NDN}} + \frac{dS_D}{T_D}} 100 = \frac{\bar{O}\Big|_{\text{Baseline NDN}} - \bar{O}}{\bar{O}\Big|_{\text{Baseline NDN}} + \frac{dS_D}{T_D}} 100.$$

  In scenarios with multiple consumers, the overall bandwidth savings, $B_{savings}$, is partially revised, by taking into

Table 4
Structure and average size of both Interest and Data, according to NDN specifications [47, 70, 86–88].

Interest Field	Size [B]
Nonce	4
Scope	1
Nack Type	1
InterestLifetime	2
Name	2 + 17.44
Selectors	2
Options	2

Data Field	Size [B]
Name	2 + 17.44
Content	2 + application payload size (5 kB to 50 MB)
Signature	33

account the considerations illustrated in Th. 3, as reported below:

$$B_{savings} = \frac{(\bar{O}\big|_{\text{Baseline NDN}} + \frac{DS_D}{T_D}) - (\bar{O} + \frac{DS_D}{T_D})}{\bar{O}\big|_{\text{Baseline NDN}} + \frac{DS_D}{T_D}} 100 = \frac{\bar{O}\big|_{\text{Baseline NDN}} - \bar{O}}{\bar{O}\big|_{\text{Baseline NDN}} + \frac{DS_D}{T_D}} 100.$$

- **Memory saving**. The memory saving is the upper bound of the amount of memory spared from PIT and CS tables by the proposed protocol for all routers of the stale disjoint path. In fact, as the Inspection procedure removes stale information from the routers of the stale disjoint path, it frees up precious space in PIT tables and spares CS from storing unuseful data. According to the discussion presented in both Sec. 3 and Sec. 4, the memory saving with respect to the baseline NDN approach is equal to:

$$M_{savings} = (A - 1)S_{PIT} + (A - 1)S_D, \tag{16}$$

where A, S_{PIT}, and S_D are the average number of routers on the stale disjoint path, the average size of a PIT entry, and the average size of a Data packet, respectively

5.1. Main parameters settings and topology models

The conducted study considers N network attachment points randomly distributed within a 10 km x 10 km urban area, corresponding to a medium-sized city. The distributed routers compose a multi-hop wireless mesh network. The average cell radius r is set to 50 m and 150 m [24, 89]. These values translate to a number of routers in the considered urban area N equal to 12732 and 1415, respectively, following $N = Area/(\pi r^2)$. On the other hand, the consumer speed is set to 3 or 30 km/h [24, 89]. Both the cell radius and consumer speed values refer to urban scenarios [89]. The average round trip time τ for wireless mesh networks is set to 0.1 s [90].

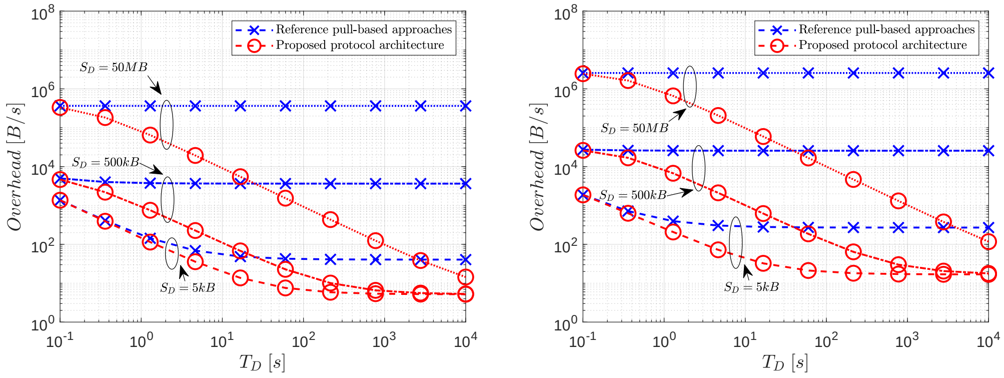
Regarding the application model, a wide range of combinations of the average application payload size is chosen between 5 kB and 50 MB and the average time interval between the generation of two consecutive contents in the range between 0.1 s and 10^4 s are taken into account. Accordingly, the resulting analysis is useful to describe the behavior of the proposed approach for many emerging applications, including HTTP [17], Big Data transfer [22, 23], aggregated sensor data [21], remote control of mobile robots [20], and adaptive video streaming [18, 19].

The size of the Subscription Request message is calculated as in [91]. The size of the exchanged messages for unuseful Data and control packets is calculated by considering the structure of Interest and Data packets [47, 86, 92] (see Table 4), an average size for the content name equal to 17.44 B [93], and the average size of the application payload, as mentioned before. The size of OpenFlow messages is calculated by considering the OpenFlow Switch Specification 1.5.1 [94].

Considering that the communication overhead also depends on the length of the path established between network node pairs, modeling the network topology becomes of paramount importance. This work considers a wireless, multi-hop, mesh, scale-free network topology with N routers, where the 1-hop neighbors are distributed according to a power law with factor $\gamma = 3$ [95, 96]. The average number of neighbors per node k is equal to $k = 2m$, where m is the number of neighbors a new node is attached to according to the preferential attachment law of the Barabasi-Albert model [96]. Different network topologies have been generated with the BRITE simulator [85]. Moreover, without loss of generality, it is assumed that each of these routers represents a network attachment point and hosts a MEC entity. The SDC is randomly attached to one of the available routers. The geo-referenced topologies generated with BRITE have been imported in MATLAB for evaluating the size of the disjoint path. Here, the position of both consumers and producer are randomly chosen at the beginning. Then, the consumers are enforced to move within the considered urban area according to the random direction mobility model. During the simulation, the consumers attach to the closest network attachment points and, therefore, trigger several handover procedures. The shortest path between any couple of nodes is calculated according to the Dijkstra algorithm. In this context, computer simulations are carried out to estimate the average number of routers on the stale disjoint path, that is A, and to verify that the average shortest path length between any nodes pair, d, is equal to $d = logN/log(logN)$ (according to [96], referring to a scale-free network topology). For each scenario, 300 different topologies are evaluated. For each topology, 100 initial positions of consumers, producer, and SDC are considered as well. Indeed, obtained results are averaged on $3 \cdot 10^4$ realizations.

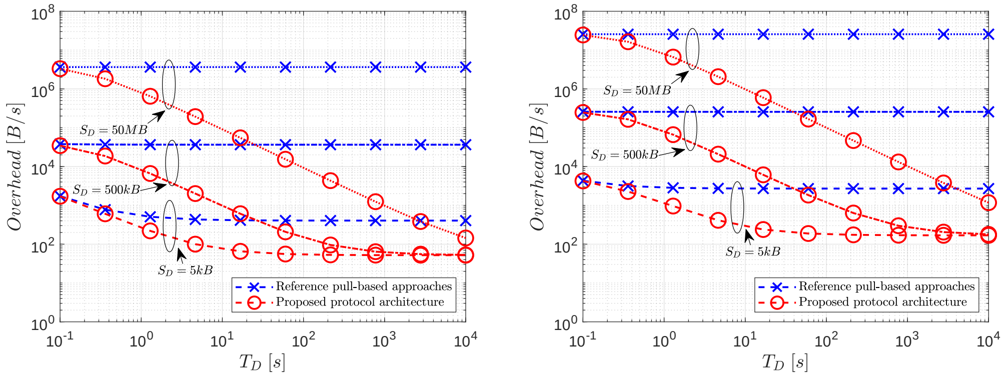
5.2. Numerical results for a scenario with a single consumer.

Fig. 8 reports the average communication overhead expected on the data plane, as a function of network size, consumer speed, and application settings. As a preliminary consideration, it is possible to observe that the average communication overhead registered by the proposed protocol architecture on the data plane decreases with T_D.



(a) $r = 150\ m,\ v = 3\ km/h$

(b) $r = 50\ m,\ v = 3\ km/h$



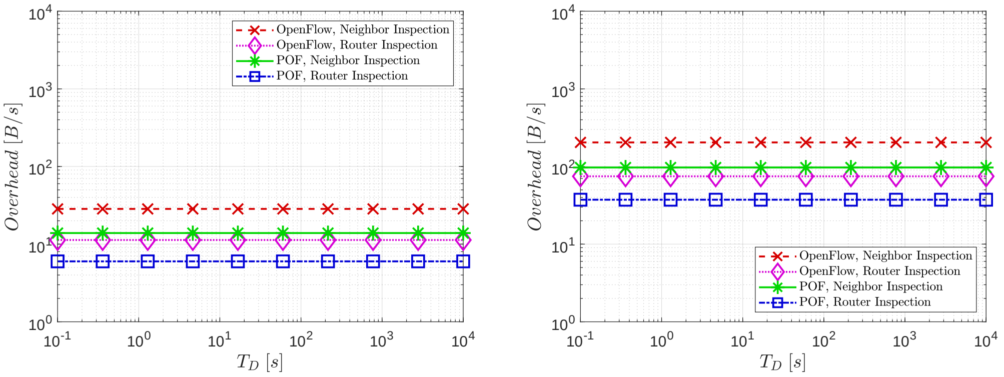
(c) $r = 150\ m,\ v = 30\ km/h$

(d) $r = 50\ m,\ v = 30\ km/h$

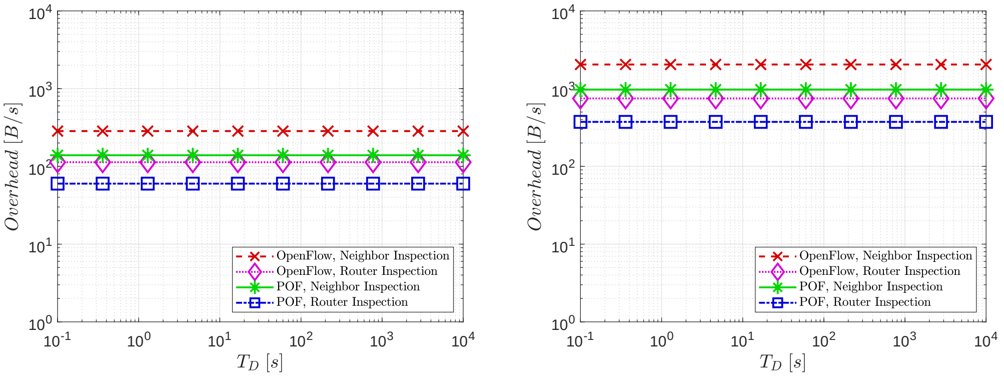
Figure 8: Average communication overhead on the data plane, as a function of network size, consumer speed, and application settings.

In fact, as the time interval between the generation of two consecutive contents increases, the SDC can clean as much wrong forwarding information as possible, thus breaking down unuseful Data dissemination. The average size of the Data packet influences the communication overhead as well. The higher the application payload size, S_D, the higher the amount of unuseful Data exchanged across the stale disjoint path. Note that the average communication overhead on the data plane increases with the consumer speed and when the average cell radius decreases. In both cases, handover episodes occur more frequently, thus augmenting the number of messages exchanged during the Re-Synchronization procedure and the amount of Data delivered across an even more number of stale links. Anyway, the most important comment emerging from the curves reported in Fig. 8 is that the proposed protocol architecture is able to always reduce the communication overhead on the data plane with respect to any other approach that exploits the pull-based approach for addressing consumer mobility in ICN deployments.

The average communication overhead generated by the proposed protocol architecture on the control plane is depicted in Fig. 9.



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$

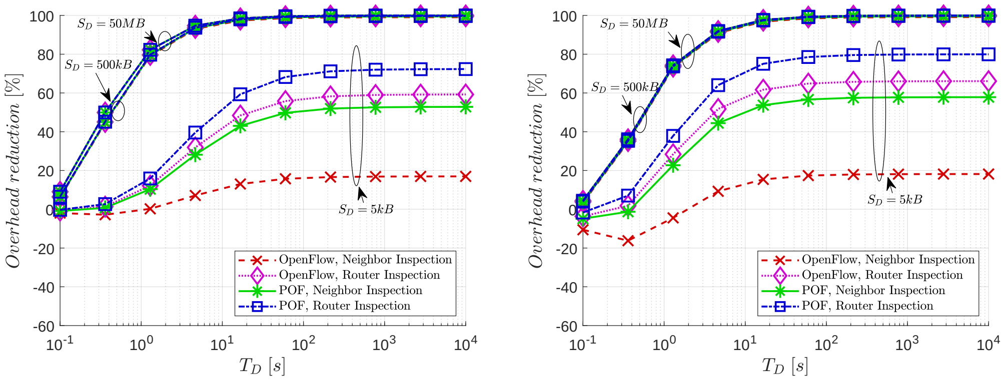


(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

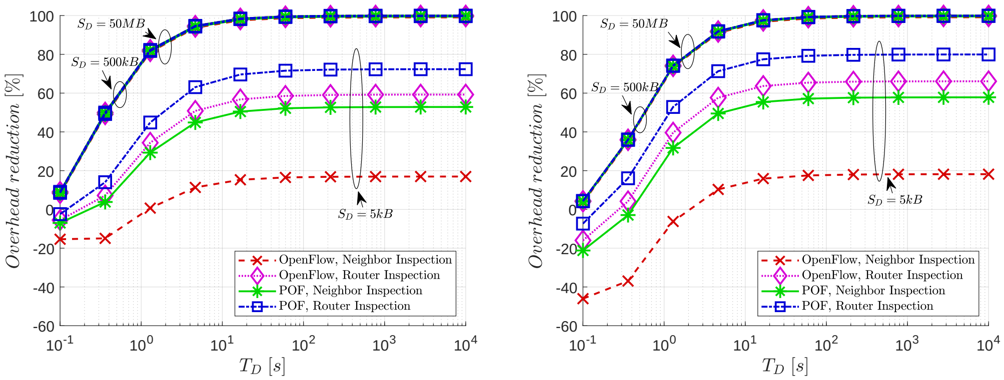
Figure 9: Average communication overhead on the control plane, as a function of network size, consumer speed, and application settings.

Obtained results identify the most performant Inspection procedure (i.e., Router Inspection against Neighbor Inspection) and its most effective implementation (i.e., OpenFlow-based against POF-based). The conducted study remarks that the average communication overhead due to control messages increases with the consumer speed or when the average cell radius decreases. In both cases, in fact, the mobile consumer changes the network attachment point more frequently and triggers more times the execution of the different Attachment and Inspection procedures. Thus, a higher number of control messages are exchanged in a unit of time. At the same time, it is possible to observe that the average communication overhead does not change with T_D. The control messages of these procedures are exchanged only once during a cell residence time, hence independently from T_D. Regarding the Inspection procedure, the Router Inspection scheme ensures a lower impact on the communication overhead, because of its ability to directly inspect the routers belonging to the stale disjoint path. On the other hand, the POF-based implementation of the control plane always achieves better performance and an overhead reduction ranging from 41.17% to 51.13% with respect to an implementation based on the conventional OpenFlow protocol. This clearly demonstrates the evident benefits offered by a control plane fully implemented through information-centric primitives.

The total overhead reduction is reported in Fig. 10. Results fully confirm the unique ability of the proposed protocol architecture to reduce the communication overhead in all the considered scenarios. For applications with limited packet size, the contribution due to control messages becomes more significant against the effect of the dissemination of unuseful Data. Indeed, regarding the scenario with $S_D = 5kB$, reported curves show that the POF-based implementation of the Router Inspection procedure always achieves better performance with respect to other implementations of the control plane. In other cases, an overhead reduction is almost due to the behavior of the data plane. Specifically, a reduction of up to 99.99% is achieved in those scenarios where the SDC is able to minimize (or at most erase) the waste of bandwidth due to the dissemination of Data packets across the links belonging to the stale disjoint path (i.e., when T_D and S_D increase, or the cell radius r decreases, or consumer speed v increases).



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$

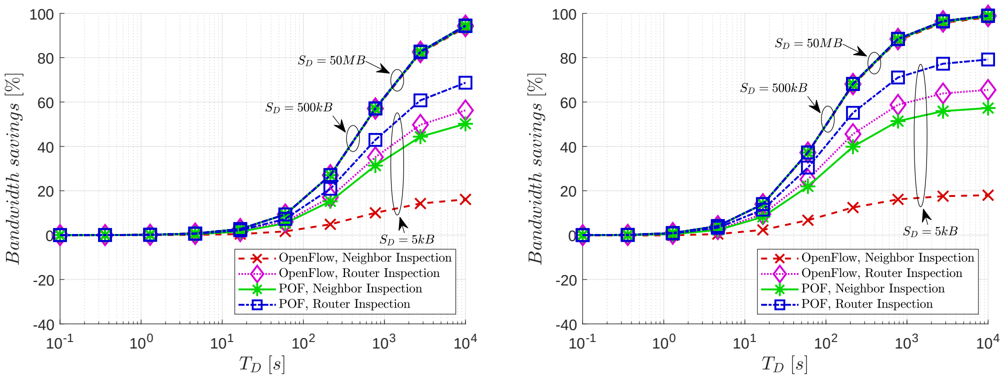


(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

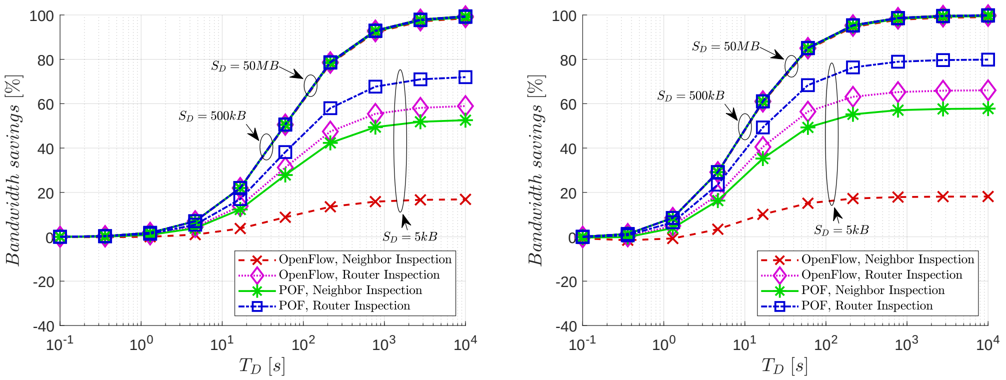
Figure 10: Reduction of the average communication overhead, as a function of network size, consumer speed, and application settings.

Fig. 11 shows the overall bandwidth savings. Once again, results demonstrate the great performance gain offered by the protocol architecture presented in this work. Specifically, bandwidth savings up to 99.9% are registered in those scenarios where the SDC can minimize (or at most erase) the waste of bandwidth due to the dissemination of Data packets across the links belonging to the stale disjoint path (i.e., when T_D and S_D increase, or when the average cell radius r decreases and the consumer speed v increases).

Finally, Tab. 5 reports the memory savings offered by the proposed protocol architecture, calculated by considering an average size of PIT entries, that is S_{PIT}, equal to 275 B [97]. Surely, the memory savings increase with the average size of Data packets, S_D. At the same time, it is influenced by the average cell radius r. It is already explained that an increment of the average cell radius brings to lower network size. When the network size increases, the length of the stale disjoint path increases as well. Here, the number of PIT entries erased by the Inspection procedure increases as well.



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$



(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

Figure 11: Bandwidth savings, as a function of network size, consumer speed, and application settings.

Table 5
Total amount of memory savings in both CS and PIT.

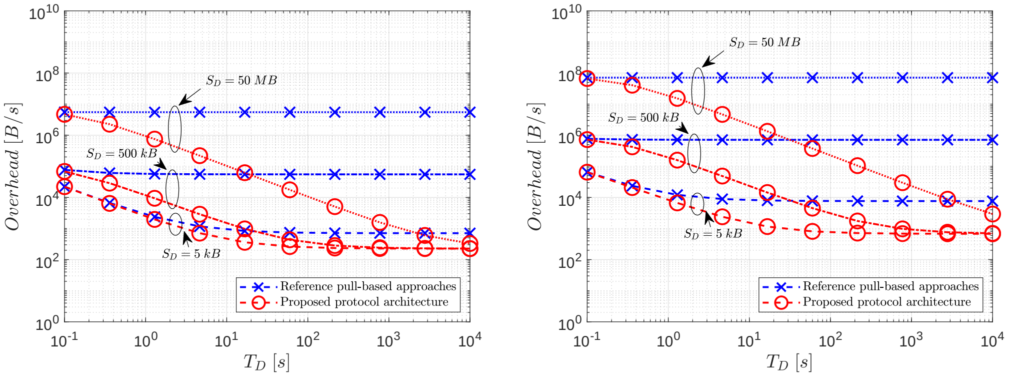
		S_D		
		5 kB	500 kB	50 MB
Average cell radius	r= 50 m	25.5 kB	2.42 MB	242 MB
	r= 150 m	10.9 kB	1.03 MB	103 MB

5.3. Numerical results for a scenario with multiple consumers.

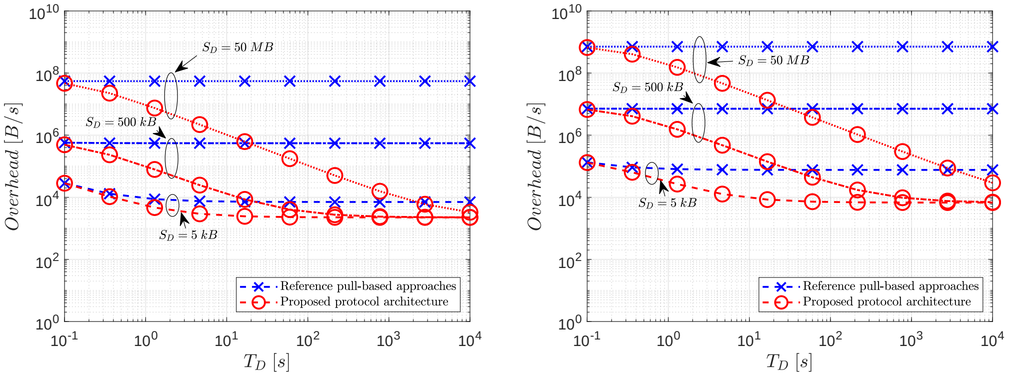
This Section describes the behavior of the proposed protocol architecture in scenarios with multiple consumers.

First of all, Fig. 12 and Fig. 13 report the average communication overhead expected on the data plane, when the number of mobile consumers is equal to 40 and 160, respectively. In line with all the comments discussed before, it is possible to observe that the average communication overhead on the data plane decreases when the time interval between the generation of two consecutive real-time contents T_D increases, the cell radius r increases, the consumer speed v decreases, and the application payload size S_D decreases. The number of mobile consumers affects the average communication overhead expected on the data plane as well. In fact, the higher number of mobile consumers, the higher number of handover episodes managed within the multi-hop wireless mesh network. This, in turn, generates a greater amount of stale disjoint links and a consequent increment of the communication overhead due to both Re-Synchronization and Data Exchange procedures.

The same considerations can be formulated by observing the average communication overhead expected on the control plane, as reported in Fig. 14 (for the scenario with 40 mobile consumers) and Fig. 15 (for the scenario with 160 mobile consumers). Therefore, the average communication overhead on the control plane decreases when the cell



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$

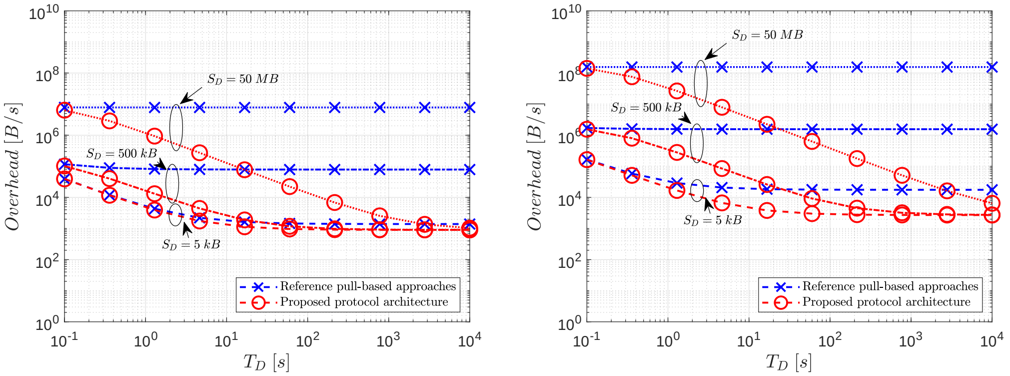


(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

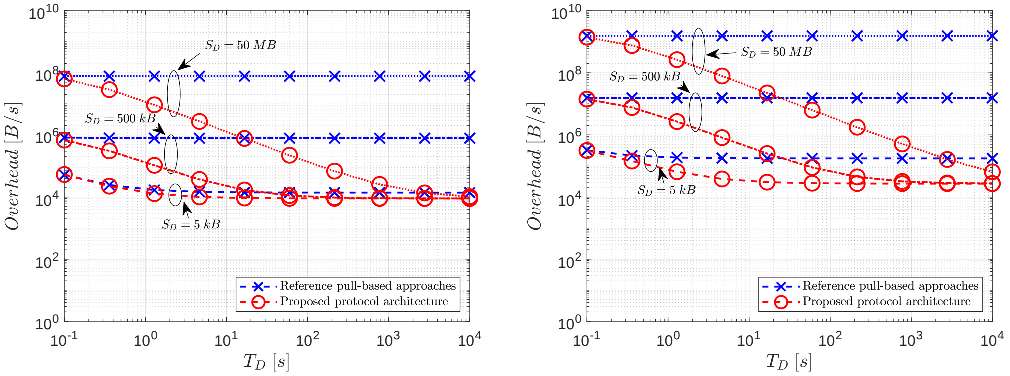
Figure 12: Average communication overhead on the data plane with 40 mobile consumers, as a function of network size, consumer speed, and application settings.

radius r increases, the consumer speed v decreases, and the application payload size S_D decreases. Similarly to the scenario with a single consumer, the average communication overhead on the control plane does not change with T_D, as the procedures are executed only once during a handover. In addition, as for the data plane, the higher number of mobile consumers, the higher number of messages generated by Attachment and Inspection procedures and delivered through the control plane. Nevertheless, it is very important to remark that, even in the case of multiple consumers, the POF-based implementation of the control plane still registers an evident overhead reduction, which ranges from 29.36% to 50.16% with respect to the implementation based on the conventional OpenFlow protocol. Once again, this demonstrates the effectiveness of a control plane fully implemented through information-centric primitives.

Fig. 16 and Fig. 17 report the average overhead reduction expected for scenarios with 40 and 160 mobile consumers, respectively. The benefits highlighted in scenarios with a single consumer are still evident in most cases. When the application payload size is equal to $500kB$ and $50MB$, for example, the proposed protocol architecture ensures an overhead reduction of up to 99.99%. Moreover, the adoption of the Routing Inspection procedure and a POF-based implementation of the control plane always guarantee the best performance. On the contrary, the results also remark that, in scenarios with lower network size, lower traffic load, and a very high number of mobile consumers asking for the same real-time contents, the amount of bandwidth consumed on the control plane tends to reach (or in some cases exceeds) the overhead saved on the data plane. However, the adoption of the Routing Inspection procedure and a POF-based implementation of the control plane emerge as suitable choices also in these extreme conditions, while proving that the proposed protocol architecture still offers unique capabilities in the transparent and flexible management of control and communication functionalities in a multi-hop wireless network. The analysis of bandwidth savings reported in Fig. 18 (for the scenario with 40 mobile consumers) and 19 (for the scenario with 160 mobile consumers) further confirms the previous considerations.



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$



(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

Figure 13: Average communication overhead on the data plane with 160 mobile consumers, as a function of network size, consumer speed, and application settings.

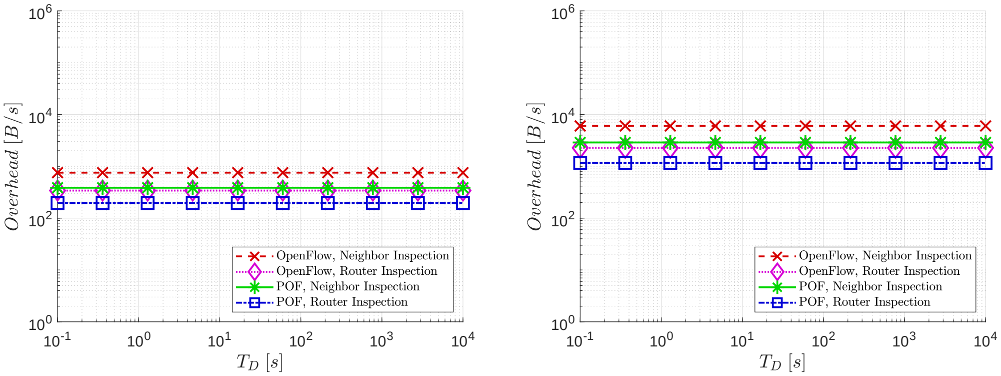
Table 6
Total amount of memory savings in both CS and PIT with 40 mobile consumers.

		S_D		
		5 kB	500 kB	50 MB
Average cell radius	r= 50 m	17.6 kB	1.67 MB	167 MB
	r= 150 m	4.10 kB	0.389 MB	38.9 MB

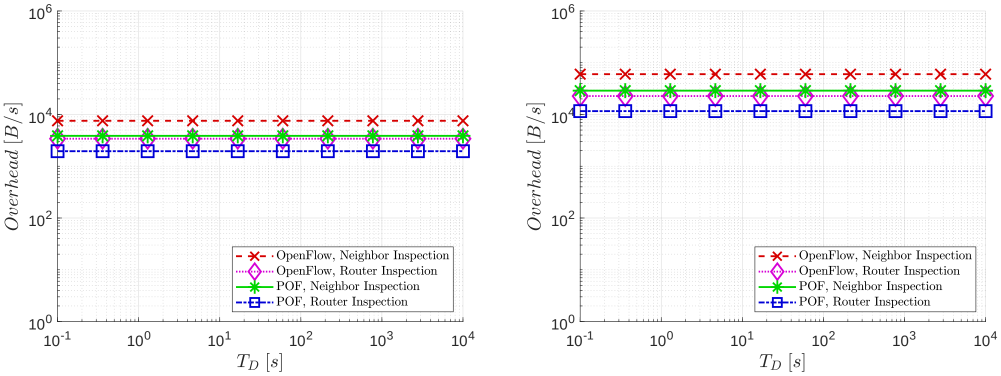
Table 7
Total amount of memory savings in both CS and PIT with 160 mobile consumers.

		S_D		
		5 kB	500 kB	50 MB
Average cell radius	r= 50 m	9.68 kB	0.918 MB	91.8 MB
	r= 150 m	1.46 kB	0.138 MB	13.8 MB

To conclude, Tabs. 6 and 7 report the memory savings obtained by the proposed protocol in a scenario with 40 and 160 mobile consumers, respectively. The results report that less memory can be spared throughout the wireless mesh network as the number of mobile consumers grows. This is due to the aggregation of requests in NDN, which intrinsically reduces the waste of memory as the number of consumers in the same network grows. But, in any case, the conceived approach still continues to offer some benefits also in this perspective.



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$

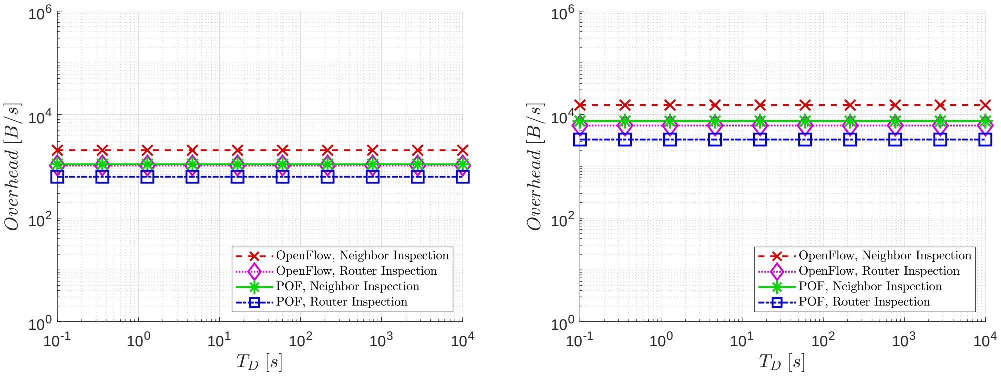


(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

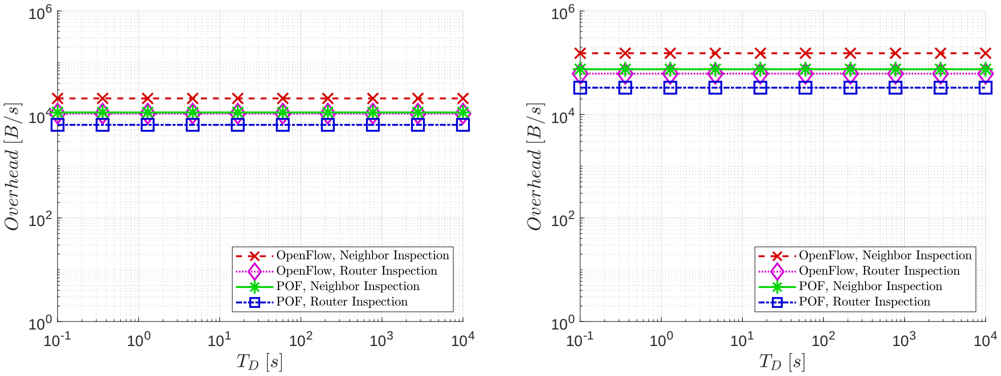
Figure 14: Average communication overhead on the control plane with 40 mobile consumers, as a function of network size, consumer speed, and application settings.

6. Conclusion

This work conceived a novel protocol architecture that successfully integrates and properly customizes the key functionalities of Information-Centric Networking, Multi-access Edge Computing, and Software Defined Networking paradigms, in order to address consumer mobility, improve network performance and guarantee a better (and fully information-centric) management of network control operations. The impact of the conceived protocol architecture to the communication overhead has been analytically formulated and numerically evaluated in scenarios with different topology, mobility, and application settings, as well as various numbers of mobile consumers. Results demonstrated that the proposed approach achieves a reduction of the communication overhead up to 99.99% on the data plane, an overall bandwidth saving up to 99.93%, and a not negligible memory saving in intermediary routers. At the same time, the adoption of information-centric communication primitives for the control plane ensures an overhead reduction ranging from 29.36% to 51.13% with respect to an implementation based on the conventional OpenFlow protocol. Only in extreme scenarios with lower network size, lower traffic load, and a very high number of mobile consumers asking for the same real-time contents, the amount of bandwidth consumed on the control plane resulted comparable with respect to the overhead saved on the data plane. Future research activities will investigate the performance of the proposed approach through experimental testbeds, implementation into flexible architectures (exploiting mobility prediction only when it is available) and next generation software-defined architectures (i.e., NG-SDN). Further analysis will also consider different protocols for the southbound interface (e.g., P4/XDP and CAPWAP) and different specifications for the OpenFlow protocol stack, while targeting a different set of key performance indexes (e.g., energy consumption, latency, throughput) through event-driven network simulators, and producer mobility.



(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$



(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

Figure 15: Average communication overhead on the control plane with 160 mobile consumers, as a function of network size, consumer speed, and application settings.

Acknowledgments

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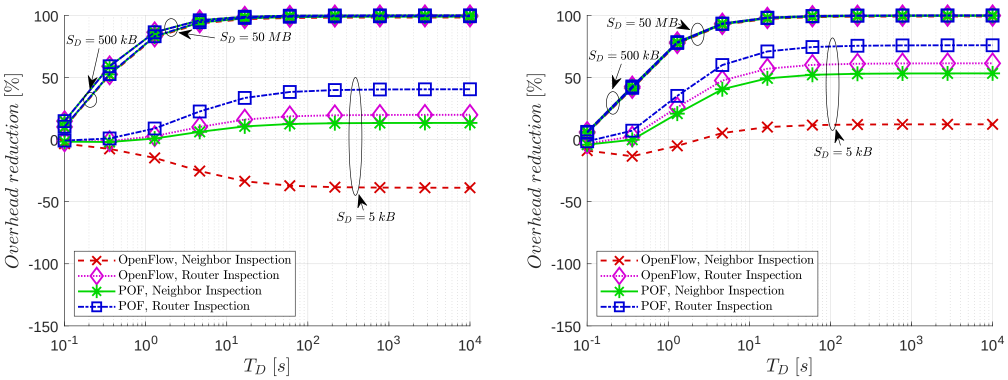
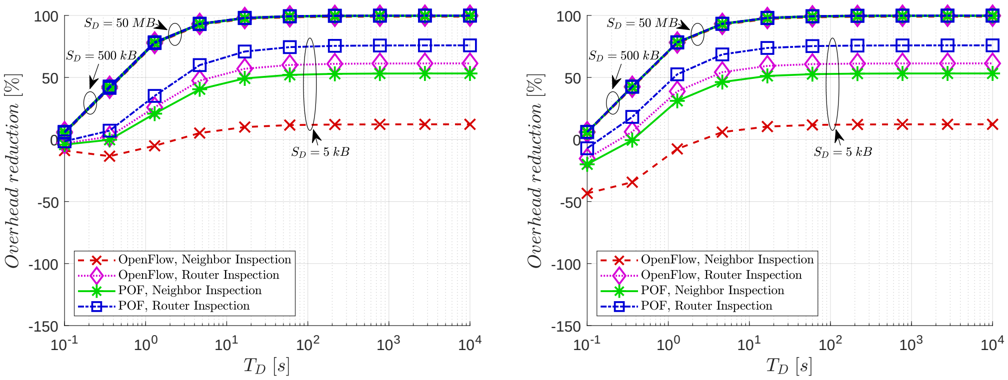


(a) $r = 150\ m,\ v = 3\ km/h$ (b) $r = 50\ m,\ v = 3\ km/h$



(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

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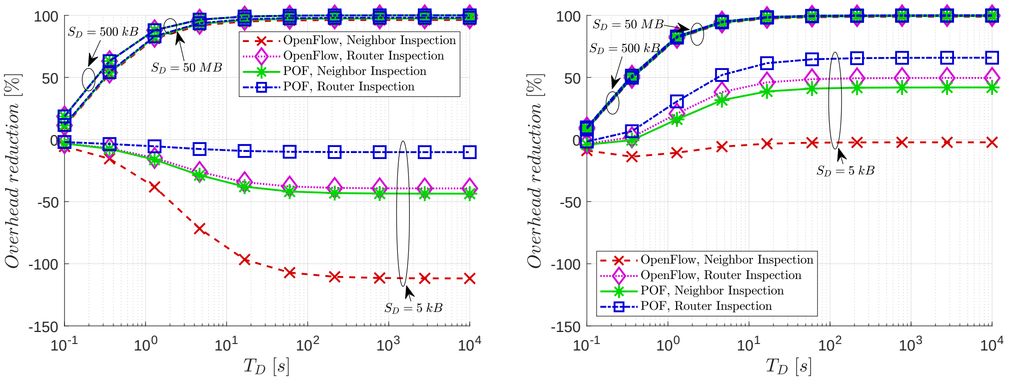

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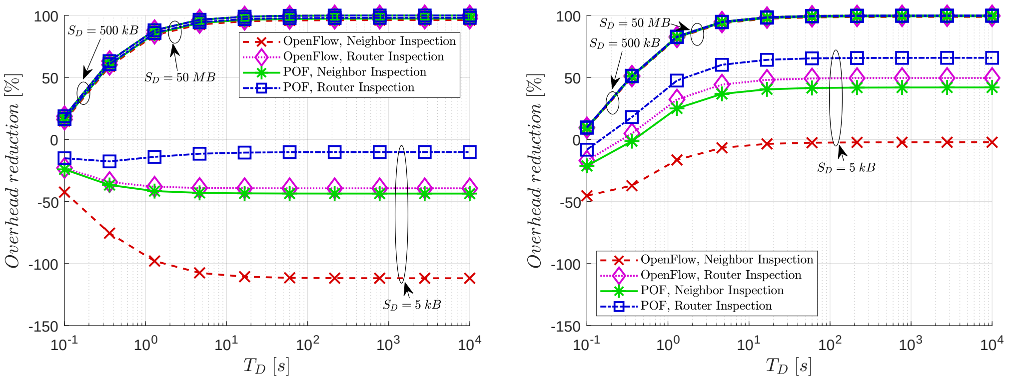

(c) $r = 150\ m,\ v = 30\ km/h$ (d) $r = 50\ m,\ v = 30\ km/h$

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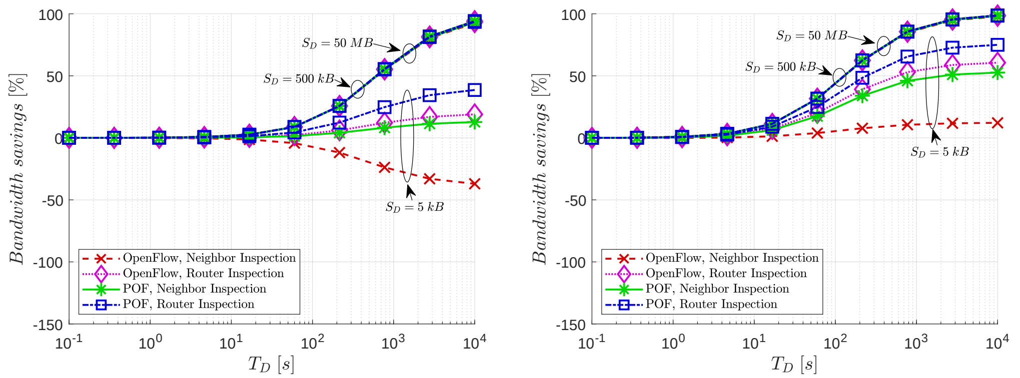

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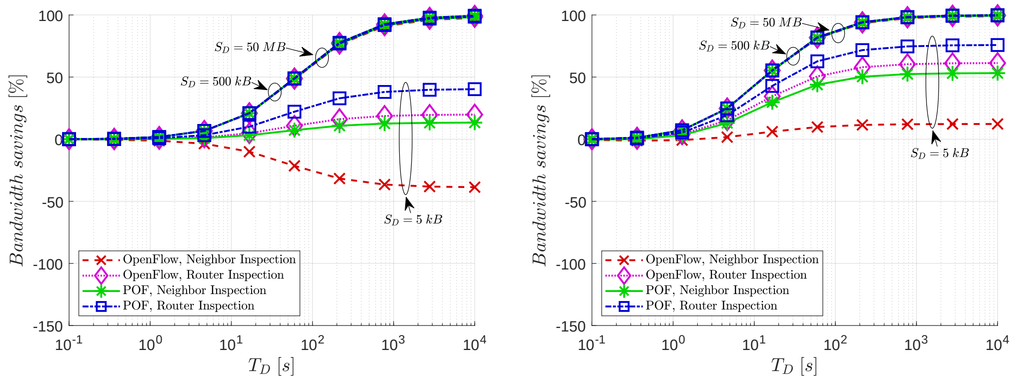
(b) $r = 50\ m,\ v = 3\ km/h$



(c) $r = 150\ m,\ v = 30\ km/h$

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Figure 18: Bandwidth savings with 40 mobile consumers, as a function of network size, consumer speed, and application settings.

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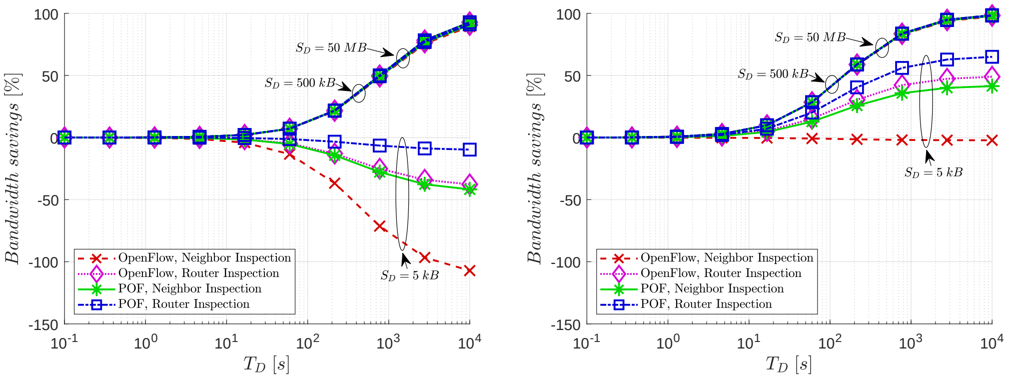

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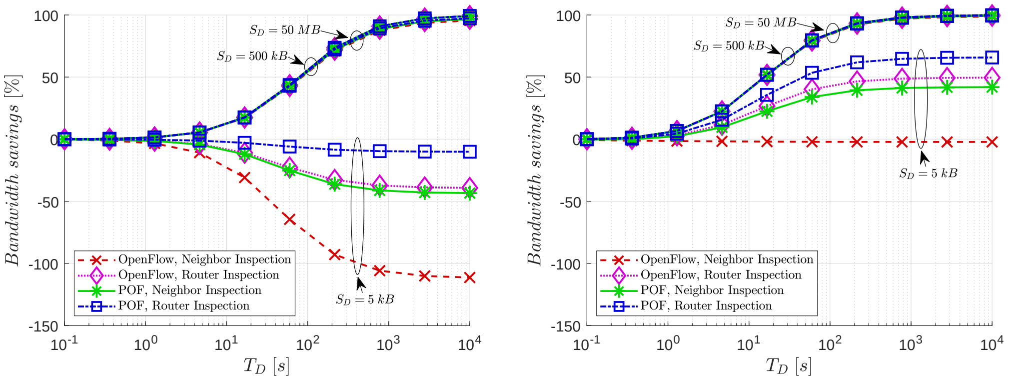

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