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Information-centric publish-subscribe mechanisms for Intelligent Transportation Systems

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***Abstract*—Emerging services for Intelligent Transport Systems put the information content at the centre of the communication process, require a seamless support of mobile users, and target a real-time and asynchronous data dissemination. The Information-Centric Networking paradigm has all the potentials to fulfill these requirements, thanks to its ability to distribute contents through publish-subscribe communication mechanism, also in mobile conditions. Unfortunately, most of publish-subscribe models proposed in the literature consider static scenarios. The work presented herein formulates two publish-subscribe schemes, based on the *pull-based* and *push-based* approaches, discusses their behavior through simplified examples, and evaluates the communication overhead they incur in realistic scenarios through computer simulations.**

I. Introduction

The Internet of Things (IoT) emerged as a promising communication paradigm, allowing an ubiquitous connectivity among smart devices deployed worldwide [1]. It became a key enabling technology for effectively implementing Machine-to-Machine (M2M) services in different domains, including home, enterprise, healthcare, urban, energy, logistics and transportation, education, and entertainment [2]-[4]. In this context, many works in the literature already demonstrated the enormous impact that the IoT concept has on the Intelligent Transport System (ITS) field. IoT, in fact, can be used to manage traffic control, energy consumption, safe and secure driving, and fleet tracking (just to name a few) [5][6][7].

Emerging M2M services for ITSs share the following key characteristics: (1) the information content covers a central role in the communication, so that users are more interested in retrieving data rather than communicating with a given node [8]; (2) the communication infrastructure is called to offer a seamless support of mobile users, that should not experience any service interruption when moving across different access networks [9]; and (3) being real-time and asynchronous, contents require an efficient and scalable dissemination process, based on the publish-subscribe communication strategy [10].

ITS architecture is standardized by various organisations (e.g ISO [11], ETSI [12]), but they are based on the classic host-centric Internet Protocol (IP) network layer. Unfortunately, the current Internet architecture is not able to effectively fulfill all the requirements. Paved on the host-centric model, it intrinsically relies on the creation of host-to-host connection, thus experiencing a number of issues related to mobility, scalability, security, content availability, location-dependence, and fault-tolerance [13]. In order to overcome these limitations, the recent Information-Centric Networking (ICN) paradigm is driving the formulation of the so called Future Internet, by introducing flexible and efficient mechanisms for content dissemination [14]. Specifically, with ICN, each content is identified through a name that does not contain anymore a reference to its location and any user request is processed by the network by means of specific name resolution and/or routing-by-name approaches. As a result, ICN provides asynchronous communications, built-in security capabilities, and Quality of Service (QoS) management, as well as a native support for mobility, multipath, and multicast communications [15][13].

Several works in the literature already investigated and evaluated the adoption of ICN communication primitives in ITSs. The main topics of interest include high-level evaluation of ITS use cases, namespace design, caching and routing-by-name algorithms, optimized delivery of data, and protocol stack implementation [16]-[27]. At the same time, however, only few preliminary contributions (i.e., [28][29]) focused on the design of publish-subscribe communication schema in the ITS field, thus leaving the space for new proposals in this direction.

Based on these premises, the work presented herein intends to provide an important step ahead of the current state of the art, by addressing the design and the evaluation of ICN-based publish-subscribe communication schemes for ITSs. The envisaged scenario considers a moving vehicle that is interested in fetching data from a remote Control Centre, according to the publish-subscribe mechanism. To this end, two different approaches are formulated: *pull-based* and *push-based* (they extend the baseline solutions already proposed in the literature, i.e., [30]-[34], but for static environments). The former assumes that the user continuously polls the remote server for retrieving any update of the desired content. The latter one, instead, intends to establish a stable communication channel with the remote server, that delivers contents without being continuously solicited. In both cases, the maintenance of a communication path between the moving vehicle and the remote Control Centre brings to a not negligible communication overhead, due to control messages exchange and extra data transmission. Indeed, after having illustrated, through examples, the meaning of these two contributions, such a communication overhead is evaluated through computer simulations. Realistic scenarios with different network deployment settings,

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user speeds, and applications are modeled. Obtained results demonstrate that the communication overhead grows with the user speed and the density of network access points, while it remains quite invariant regarding the bitrate of considered applications. Furthermore, the pull-based approach registers the lowest communication overhead.

The rest of the paper is structured as follows: Section II provides some technical details related to a specific implementation of the ICN, namely Named-Data Networking (NDN), and reviews the related state of the art on publish-subscribe communication approaches. Section III describes the conceived *pull-based* and *push-based* schemes and presents the concept of the communication overhead through concrete examples. Simulations results are discussed in Section IV. Finally, Section V provides conclusion and future research activities.

II. State of the Art

The Information-Centric Networking (ICN) communication paradigm was developed in many concrete network architectures, that are Data-Oriented Network Architecture (DONA), Network of Information (NetInf), Publish Subscribe Internet Technology (PURSUIT), CONVERGENCE, Named-Data Networking (NDN), MobilityFirst, and COntent Mediator architecture for content-aware nETworks (COMET) [13]. Without loss of generality, this work focuses on NDN, which represents the solution that got most of the worldwide attention [35].

NDN leverages a receiver-driven architecture and only two kind of messages are allowed: $Interest$ and $Data$ packets. The communication process envisages that: (1) the user, that wants to retrieve a content, issues an $Interest$ packet; (2) the network delivers the user request towards the node able to provide the corresponding answer; (3) the content is stored within a $Data$ packet and is sent back to the user through the reverse path of the $Interest$ packet. Now, to accomplish this process, each NDN node is equipped with three main architectural elements: Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB). Specifically, the Content Store (CS) is a memory that caches incoming $Data$ packets; the Pending Interest Table (PIT) tracks user requests not yet satisfied; the FIB maps content names and output interface for supporting routing operations.

The example depicted in Fig. 1 describes the NDN mechanism. In the considered scenario, a vehicle communicates with the Control Centre, by expressing an $Interest$ for a particular content (e.g. traffic or weather information). When a NDN node receives this $Interest$, it executes the following operations: first of all, the CS is looked up in order to verify if the received request can be satisfied locally; if so, the node sends back the requested $Data$. Otherwise, the PIT is looked up to check if the same $Interest$ has been previously forwarded but it is still unsatisfied. In this case, the received $Interest$ is discarded, and its arrival face is added to the incoming faces of the matched PIT entry. On the contrary, if a matching entry is not found in the PIT, the FIB is examined through a Longest Prefix Match (LPM) operation, in order to find potential routes to forward the $Interest$ through. For what concerns the reception of a $Data$ packet, instead, the PIT is the first structure to be checked, because only if there is a matching pending entry, the packet will be processed and sent back to its requester(s); otherwise, it will be discarded.

From the provided example, it is possible to understand that a multi-hop communication path is established between the user and the node able to provide the requested content. However, it is important to highlight that a timeout is assigned to $Interest$ packets stored within the PIT tables of intermediate routers. Therefore, such a multi-hop communication path remains active until the corresponding $Data$ packet is sent back to the user or the $Interest$ lifetime expires.

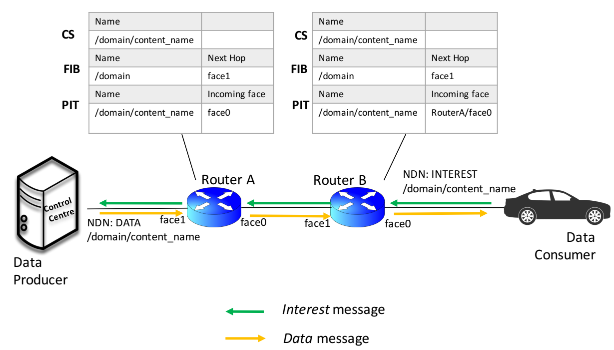


Fig. 1. An example showing NDN functionalities.

NDN natively supports the request-response communication paradigm. For the publish-subscribe scheme, instead, some tricks have to be introduced. When the publish-subscribe schema is used, a consumer sends a subscription request for the topic it is interested in. Then, as soon as a new content belonging to that topic is generated, it is delivered to the subscribed user. Many solutions were already formulates for static environments. In general, they adopts two different approaches, that are *pull-based* and *push-based*. In the first one, the consumer sends a new request as soon as a content is retrieved [30]. Instead, in the second one, the consumer establishes a communication channel with the producer, thus retrieving contents without continuously sent solicitations [31]-[34].

For the best of the authors knowledge, only two contributions investigate solutions for mobile scenarios [29] and [28]. The work proposed in [29] extends the baseline NDN architecture by introducing broker nodes. Publisher and consumer register theirselves to the broker node by sending a specific $Interest$ packet. On the producer side, the $Interest$ packet stores the name of the content it provides; on the consumer side, the $Interest$ packet stores the name of the content to retrieve. Then, the broker node answers by delivering a $Data$ packet of confirmation. The broker continuously polls the producers by issuing $Interest$ packets (e.g., each request is sent immediately after that a new content is received). The broker informs the user every time a new content is available, thus allowing it to retrieve the desired data through the conventional request-response mechanism. To handle mobility, the consumer re-issues the $Interest$ message to the broker every time it changes the network attachment point. The work presented in [28] introduces a new network element, namely Rendezvous Point (RP), other two new messages, namely $Publish$ and $Subscribe$, and a new table to handle subscriptions, namely Subscription Table (ST). During the subscription process, the user sends a $Subscribe$ message to the reference RP. Such a message is also stored in ST tables of intermediate routers. Then, a producer delivers a new content to the RP through the $Publish$ message. Such a content is delivered to the subscriber according to the information stored in ST tables. Also in this case, to support consumer mobility, the subscription request is simply periodically renewed.

III. Publish-subscribe approaches in case of consumer mobility

The reference scenario considered in this work is depicted in Fig. 2. A mobile vehicle is interested in retrieving content from the remote Control Centre, according to the publish-subscribe communication schema. Moreover, it is connected to the core network NDN through a wireless communication technology (i.e., each network attachment point, represented by the Road Side Unit, acts as one of the node of the NDN network). Usually, vehicle and remote Control Centre are not directly connected. In order to have a successful data delivery, a multi-hop communication path has to be established between them. During the time, the vehicle frequently changes the network attachment point. As a consequence, user mobility implies that the multi-hop communication path established between vehicle and remote Control Centre has to be re-established.

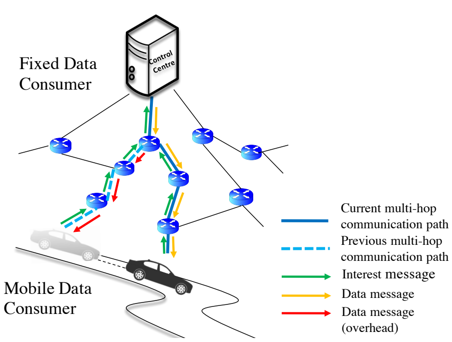


Fig. 2. Reference scenario.

This work formulates two mechanisms enabling publish-subscribe communication schema in NDN networks. They leverage the *pull-based* and the *push-based* approaches, as described in Section III-A and Section III-B, respectively. Both of them introduce specific strategies for re-establishing the multi-hop communication path between vehicle and remote ITS server. The resulting protocols generate a not negligible communication overhead, as discussed in Section III-C.

A. Pull-based approach

The conceived *pull-based* approach extends the solution presented in [30] by introducing the support of mobility.

At the beginning, the vehicle sends a window of W $Interest$ packets to the remote Control Centre. Every time a new content is received, the window of pending requests moves forward and the vehicle sends a new $Interest$ packets to the remote Control Centre.

It is important to note that the window size W should be properly set in oder to guarantee an optimized flow control. Let T_{RTT} and T_G be the Round Trip Time and the average generation time interval between two consecutive contents, respectively. The window size should be set as: $W = \left\lceil \frac{T_{RTT}}{T_G} \right\rceil$. Anyway, by considering that the Round Trip Time is usually of order of milliseconds and that $T_G >> T_{RTT}$, it is possible to simplify the protocol implementation by setting $W = 1$. In this way, the mechanism results to be a stop-and-wait automatic repeat-request (ARQ).

The timeout assigned to $Interest$ packets stored in PIT tables is set to T_G. In this case, in fact, it is possible to avoid that PIT entries are deleted before the reception of a corresponding $Data$ packet.

Finally, to ensure that the communication path between vehicles and remote Control Centre is maintained also in mobile conditions, a new $Interest$ packet should be sent by the user every time it changes the network attachment point.

B. Push-based approach

The designed *push-based* approach takes into account the concept of semi-persistent $Interest$ packet [34].

Similarly to the previous approach, also in this case the $Interest$ packet is sent by the vehicle to establish a multi-hop communication path with the remote Control Centre. In this solution, however, $Interest$ packets are semi-permanent. Differently from the conventional implementation of the NDN protocol, a semi-persistent $Interest$ packet is not deleted from the PIT table even if a corresponding $Data$ packet is sent back to the user. On the contrary, it is deleted only when its timeout T_{out} expires. The resulting approach is able to establish a stable communication channel with the remote server, that delivers contents without being continuously solicited.

In this context, to ensure that the communication path between vehicles and remote Control Centre is continuously updated also in mobile conditions, the user is in charge of sending the $Interest$ packet when it changes the network attachment point or every timeout T_{out}.

C. Discussion on the communication overhead

As already introduced at the beginning of this Section, a publish-subscribe communication scheme brings to a not negligible communication overhead. In this work, the communication overhead is defined as the total amount of bits due to both control messages and extra data transmission, issued during a unit of time.

Sections III-A and III-B demonstrated how the multi-hop communication path is established by sending an $Interest$

packet from the vehicle to the remote server. Thus, $Interest$ packets act as control messages and provide the first contribution to the communication overhead.

It is extremely important to remark that when a new multi-hop path is established between vehicle and remote server, the previous one could be still active. This is true till the information stored within PIT tables of intermediate routers, and related to the user request previously sent, will be erased. If the *pull-based* approach is used, the PIT entry is cancelled when the intermediate node receives a corresponding $Data$ packet and sends it back to the user. In the *push-based* approach, instead, the PIT entry is erased only when the assigned timeout expires. In any case, two important remarks can be made about user mobility. First, more than one multi-hop path can coexist at the same time. Second, depending on the network topology, such multi-hop paths could be partially overlapped. Now, when a new content is generated by the remote Control Centre, it is delivered across all the multi-hop communication paths active in the NDN network. Accordingly, $Data$ packets delivered through the links belonging to stale paths that are not included in the new one, represent the second contribution to the communication overhead.

Figure 3 shows an example that qualitatively illustrates messages affecting the communication overhead and generated by the *pull-based* approach. A vehicle connects to different network attachment points in the following time instants: t_1, t_2, and t_3. From the figure, it is possible to observe that the user sends $Interest$ packets every time a new content is received or when it attaches to a new network node. All of these messages represent the first contribution to the communication overhead. From the figure, it is also possible to observe that when the 4-th content is generated, two paths are active (i.e., the one established at t_1 and the other established at t_2). Indeed, $Data$ packets delivered across the links of the first path that are not integrated in the latter one represent the second contribution to the communication overhead. Similar consideration can be done also for the 5-th content.

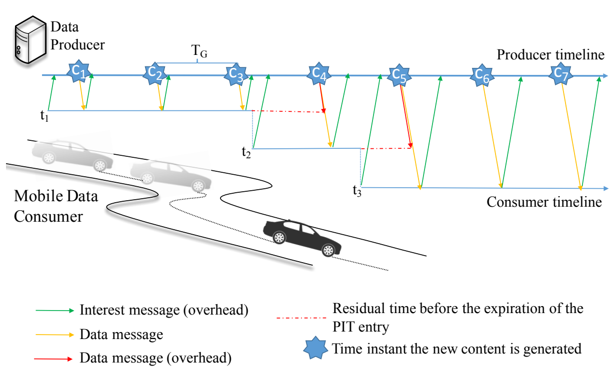


Fig. 3. Message sequence chart showing $Interest$ and $Data$ packets exchanged when the *pull-based* approach is used.

Figure 4 shows an example that qualitatively illustrates messages affecting the communication overhead and generated by the *push-based* approach. Also in this case, the vehicle connects to a new network attachment point in the time instants t_1, t_2, and t_3. The user sends an $Interest$ packet every T_{out} or every time it changes the network attachment point. As expected, these messages represent the first contribution to the communication overhead. The proposed example assumes that T_{out} is configured in order to have no more than one stale path at each change of network attachment point. From the figure, it emerges that when the 3-th and the 4-th contents are generated, the path established at t_1 is still active. Therefore, $Data$ packets transmitted through its links produces the second contribution to the communication overhead. Similar consideration can be done also for the 5-th and the 6-th contents.

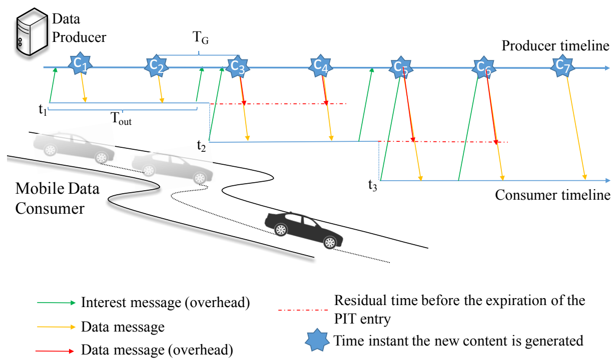


Fig. 4. Message sequence chart showing $Interest$ and $Data$ packets exchanged when the *push-based* approach is used.

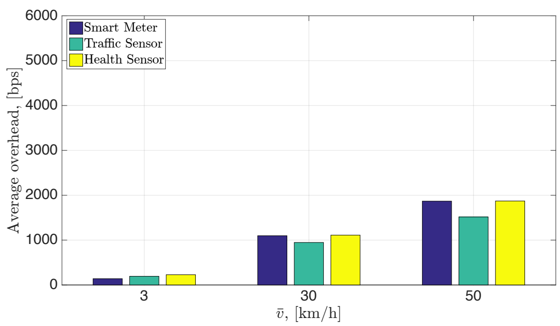
IV. Preliminary performance evaluation

In this Section, the communication overhead generated by both *pull-based* and *push-based* approaches is investigated through computer simulations.

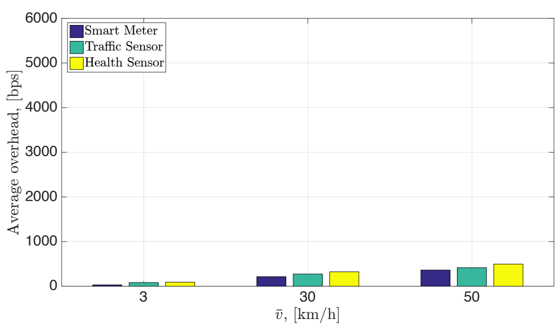
First of all, the Boston university Representative Internet Topology gEnerator (BRITE) [36] is used to generate the topologies of the NDN network. This tool is able to produce scale-free network topologies, typical used to represent the current Internet architecture [37]. For the sake of simplicity, it is also assumed that NDN nodes represent network attachment points to which a vehicle can connect. Such nodes are distributed in a geographical area of 10^6 m^2 and, in line with [38], different urban scenarios are considered. To evaluate the impact of the density of network attachment points, the total number of NDN nodes is chosen in order to ensure an average coverage area of 50 m and 150 m. The user speed, instead, is set to 3, 30, and 50 km/h.

At the application layer, three different services are considered: smart meter, traffic control, and health-care [39]. According to [40] the size of the $Interest$ packet is set to 432 bits. Nevertheless, by jointly considering information provided in [39] and [41], the size of $Data$ packets generated by smart meter, traffic control, and health-care applications is set to 18552 bit, 2424, bit, and 3440 bit, respectively. The resulting aggregate bit rate, instead, is set to 2.04 bit/s, 40.40 bit/s, and 57.33 bit/s for smart meter, traffic control, and health-care applications, respectively.

The communication overhead registered by the *pull-based* approach is reported in Figure 5. Results demonstrate that the communication overhead increases with the speed of the vehicle. When the user moves at a higher velocity, it may change the network attachment point more frequently. As a consequence, a higher number of $Interest$ packets are sent towards the remote Control Centre. At the same time, frequent handover processes provoke the generation of a higher number of stale paths, thus bringing to an increment of the contribution to the overhead due to extra data dissemination. Also, the communication overhead decreases with the average coverage area of network attachment points. In a scenario with a higher node density, in fact, handover processes happen more frequently and the number of links belonging to the multi-hop path established between vehicle and remote Control Centre increases. Thus, the total amount of bit due to control messages and extra data transmission increases as well. No significant differences are registered for the investigated applications.



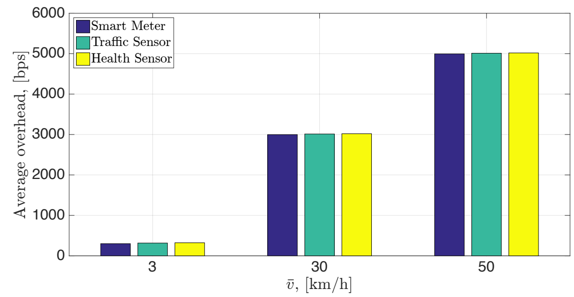
(a) r = 50 m



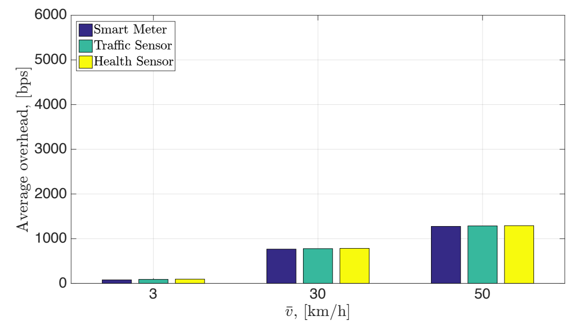
(b) r = 150 m

Fig. 5. Communication overheads related to the pull-based approach, when the average coverage area of network attachment points is equal to (a) 50 m and (b) 150 m.

The communication overhead registered by the *push-based* approach is reported in Figure 5. Also in this case, it is possible to observe that the communication overhead increases with the user speed and decreases with the average coverage area of network attachment points. For what concerns the cross-comparison between *pull-based* and *push-based* approaches, it is evident that the *pull-based* scheme always registers the lowest communication overhead. This result is due to the fact that when the *pull-based* approach is used, stale paths remain active just until the transmission of a single $Data$ packet and, as a consequence, the impact of extra data transmission, is significantly reduced.



(a) r = 50 m



(b) r = 150 m

Fig. 6. Communication overheads related to the push-based approach, when the average coverage area of network attachment points is equal to (a) 50 m and (b) 150 m.

V. Conclusion

This work formulated two publish-subscribe communication schemes for information-centric Intelligent Transport Systems. The conceived solutions leverage *pull-based* and *push-based* approaches and integrate specific tricks for supporting user mobility. A preliminary performance evaluation evaluated the impact these mechanisms have on the overall communication overhead. To this end, realistic scenarios with different network deployment settings, user speeds, and applications were modeled and investigated through computer simulations. Obtained results demonstrated that the communication overhead grows with the user speed and the density of network access points, while remaining quite invariant regarding the bitrate of considered applications. Furthermore, the pull-based approach registers the lowest communication overheads in all the investigated scenarios. Future research activities will consider scenarios where the data producer is mobile, as well as further characterize the communication overhead through analytical models.

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