Consumer Driven Information Freshness Approach for Content Centric Networking

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***Abstract*—In the last few years, the research community has witnessed the rapid development of the Information-Centric Networking (ICN) approach aiming at evolving the Internet from today's host based packet delivery towards directly retrieving information in a secure, reliable, scalable, and efficient way. The Internet of Things (IoT) concept envisions scenarios in which "smart objects" can be interconnected to enable a whole new class of applications and services, positively increasing the impact of Information and Communication Technologies (ICT). Although ICN tested scenarios have been mainly limited to multimedia and data, quoted advantages of ICN make from this architectural design a valuable approach in addressing the challenges that arise from the increasing deployment of IoT. In general, IoT applications impose stringent requirements in terms of information freshness, which can be highly impacted by the intrinsic caching mechanisms existing in ICN approaches. In the present work, the available freshness mechanism conceived as part of the Content-Centric Networking (CCN) protocol is assessed and a novel consumer driven information freshness approach is proposed to satisfy the consumers' needs while mitigating the negative effect of the freshness requirements in the overall network performance. The new mechanism was evaluated through simulation, with obtained results showing that the proposed approach leads to better performance, as compared with the available CCN freshness mechanism.**

***Keywords*—Information Centric Networking, Internet of Things, Information Freshness, Caching.**

I. Introduction

It is predictable that, within the next ten years, the Internet will be transformed into a seamless collection of networks and networked objects able to communicate, compute and coordinate. This innovation will be enabled by the embedding of electronics into everyday physical objects, making them "smart" and allowing them to efficiently integrate within the global resulting cyberphysical infrastructure [1]. The term Internet of Things (IoT) has been adopted to denote the resulting global network that interconnects smart objects and it is often used to refer also to the set of supporting technologies needed to achieve such a vision, as well as to the ensemble of applications and services leveraging such technologies to open new business and market opportunities. In this context, smart objects are more than just sensor nodes, they are interactive tools designed to accomplish specific tasks in the real world [2]. The Internet interconnecting end-user devices is expected to change to an Internet interconnecting physical objects that communicate with each other and/or with humans to provide a service. The IoT is emerging as one of the major trends shaping the development of technologies in the Information and Communication Technologies (ICT) sector at large. The shift involves the need to reconsider some of the conventional approaches commonly used in networking, computing and service provisioning/management.

The fact that IoT is increasingly focusing on data and information rather than on point-to-point communications could lead to the adoption of recently proposed Information-Centric Networking (ICN) architectures and principles. The ICN approach was pioneered in TRIAD [3] and it is currently being explored by a number of research projects (e.g., Data-Oriented Network Architecture (DONA) [4], Named Data Networking (NDN) [5], Publish-Subscribe Internet Technology (PURSUIT) [6], Network of Information (NetInf) [7]). The rapid development of ICN concepts in the last few years is one of the significant results from multiple international Future Internet research activities. The fundamental concept in ICN is to evolve the Internet from its original host-centric paradigm, in which a mapping of what users want to where it is in the network has to be done, to a completely new content-centric paradigm, in which an item of content can be directly recovered by its name, decoupling content from location. This change from host-centric to content-centric has several attractive advantages, such as network load reduction, low dissemination latency, and better energy efficiency [8]. These architectural design efforts aim to directly address the challenges that arise from the increasing demands for highly scalable content distribution, the accelerated growths of mobile devices, the wide deployment of IoT, and the need to secure the global Internet. The ICN approach is considered to be a viable solution to the challenges imposed by the predicted IoT scenarios and important research works are being conducted to deal with resulting challenges.

The contribution of this paper is twofold. First, it analyses the impact that the inherent multi-node caching mechanism of most ICN approaches imposes on IoT scenarios, considering the delay between the information generation and its consumption from the cache (e.g., information freshness). Second, it proposes a novel consumer driven information freshness mechanism, to mitigate the negative effect of the information freshness requirements in IoT-enabled ICN scenarios.

The rest of the paper is organized as follows. The principal efforts of the research community in evaluating the content centric approaches with respect to their capacity to handle the requirements imposed by the envisioned IoT scenarios are discussed in Section II. Section III provides details of the new

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consumer driven freshness mechanism for Content-Centric Networking (CCN), dealing with the information freshness mechanisms implemented in CCN and their relevance in IoT scenarios. Section IV describes the conducted experiments and discusses the results obtained. Section V concludes the paper with an overall discussion of the results and future work.

II. Related Work

The deployment of IoT-enabled ICN aspects has been being addressed by the research community, with the Internet draft in [9] considered to be a major contribution in this field. This document presents several ICN baseline scenarios and discusses relevant issues towards the application of this approach to the IoT. The use of named data is definitely identified as a key element for considering the ICN approach as bringing benefits in the deployment of IoT. By making the information visible and identifiable at the network layer, named data can be used for a more efficient management of coordination and collaboration within IoT. Some other advantages reinforcing the beneficial effect of named data on IoT have been identified by Heidemann et al. in [10]. The authors describe a software architecture that supports named data and in-network processing within an operational multi-application sensor-network.

The IoT will expose the ICN approach to a strict set of requirements which are intensified by the amount of nodes, as well as by the type and volume of information that must be handled. Marias et al. [11] provide some clarification to this issue by addressing the problem of mapping named information to an object. The high amount of nodes expected to take part in the IoT scenarios not only arises scalability challenges, but also crucial problems regarding the heterogeneity of devices taking part of the IoT. Particularly, the existence of large amounts of network devices with constrained resources in terms of power consumption, storage, computing capability and communications is expected. This issue has been coherently addressed in [12], where Song et al. propose a content-centric internetworking scheme for weak devices in which, based on the key ideas and basic models of CCN, overcapacity tasks are mapped into stronger devices. Burke et al. [13] studied lighting control over NDN, which in turn is an example of an “instrumented environment”. This application explores a new scope for ICN, which in the context of large scale content dissemination is generally discussed as opposed to control, actuation, or remote execution.

Biswas et al. [14] visualize ICN as a contextualized information-centric bus (CIBUS) over which diverse sets of service producers and consumers co-exist. The authors outline several features provided by the content-centric approach that make it suitable for different application environments such as home network (home-net), Vehicle to Vehicle (V2V), and IoT. Ravindran et al. [15] particularize how a content-centric approach may be applied in a home network environment, and emphasizes the need for a homogeneous platform to handle the diversity of devices, services, and user needs. Dannewitz in [16] argues that integrating the Augmented Internet and ICN concepts is not only feasible but highly recommended. The arguments are the result of a comprehensive discussion on how specific properties of ICN can satisfy the requirements imposed by the Augmented Internet concept, which are later generalized by analysing how such properties can be also useful in applying a content-centric approach to other use cases.

In [17], Dinh et al. propose the ICN approach as a fundamental driver for Wireless Sensor Networks (WSN). The authors leverage the capabilities of ICN and introduce some changes for achieving efficient coordination, interoperability, service discovery, and prioritized routing. A novel continuous mode for Interest packets, Continuous Interest (CI), is proposed. CI packets are not intended to be deleted after a corresponding Data packet has satisfied the interest, and consequently their lifetime is set to higher values, as compared to the conventional CCN Interest packets. A Data packet is generated and forwarded back to the corresponding requester if there are some events or changes in the sensing data. This exploration establishes a potential foundation to improve performance of WSNs while opening new avenues for future research in ICN-based IoT. Saadallah et al. [18] go forward in the area of ICN-based WSN by implementing and integrating a CCN communication stack into the Contiki operating system used for resources-constrained embedded systems and wireless sensor networks. The implementation is evaluated under varying network sizes conditions through simulation and real deployment on a testbed. Ren et al. [19] design, implement and evaluate CCN-WSN, a lightweight variant of a CCN protocol specific for WSN. Certain modifications were introduced to the CCNx protocol for dealing with the memory and computational resources constraints associated to sensor nodes and communication patterns in WSN. Authors claim that using CCN right on top of IEEE 802.15.4 provides an efficient solution and reduces overhead. In dealing with the challenge of efficient data aggregation in WSN, Teubler et al. [20] extend CCN-WSN [19] by introducing three major components: unicast faces to reduce the number of messages in a broadcast medium; forwarding service to create overlay structures on a given physical topology; and an intra-node protocol for communication between applications and the forwarding service.

Wang et al. in [21] and [22] explore an ICN approach for direct V2V communications, identifying and addressing issues such as the need of data pushing instead of pulling, and the need of well-defined application naming conventions, understandable for all the vehicles and flexible enough to allow vehicles to express exactly what kind of data they may desire.

III. A consumer driven freshness approach

CCN leverages in-network storage for caching. This feature is considered to be a common key advantage to all ICN approaches. The information made available in CCN can be retrieved from any other entity in the network holding a copy of the original packet. However, it has some drawbacks when considering IoT-like applications, where the precision of the information received could be very decisive for the adequate development of the consumer application.

A. Motivation

In IoT scenarios, new information is constantly being generated and consumers are mainly interested in the latest information. In this regard, the use of sequence numbers for naming data to be sensed does not seem to be a valid approach, as a node that joins the network at a given time willing to get the latest information, does not know which sequence number to ask for. On the other hand, an approach in which no sequence number is used, depending on how the information is named, will be also not valid for IoT purposes if it does not include a sort of timestamp in the name, as the information will be generated under the same name, although the data values will be different.

For example, a name such as "/sensorX/latestTemperature" will be interpreted by routers and cache as being the same they have already stored and the existing old information will not be updated. In this way, unwanted behaviours may occur, such as the first router always replying to the consumer with old information instead of forwarding the interest towards the source, or even worse, the consumer's cache itself may always answer.

To address this issue, CCN includes a freshness parameter (FreshnessSeconds) in Data packets (Content Objects) that establishes how many seconds a certain packet will be allowed to be held in the network Content Stores (i.e., before marking it as stale), thus allowing the information producers to have some control over the packets removal process from network. However, if no freshness value has been adopted or defined by the producer, the consumers will not be able to get new content unless in accordance with the cache replacement policies of the routers.

Different consuming applications may have different information freshness requirements from the same source of information. In order to provide support to applications involving consumers with different freshness requirements, it seems appropriate to set the freshness parameter to the lowest value among those required by consumers. However, lower freshnesses will cause the information to be retrieved from the source more frequently (i.e., fewer cache hits). This could present a low efficiency in cases where the active time of applications with more strict freshness requirements are lower than the active time of the application that can handle the higher values of freshness, or where applications simply do not run within the same window of time. Moreover, it should be noticed that it is not always possible to know beforehand the freshness that will be required by a certain consuming application. The establishment of an appropriate value of freshness has particular importance when considering constrained resources and battery powered producers, as it is common for sensors in IoT, where establishing each communication has a cost in terms of battery lifetime.

It is in this context that we propose a consumer driven freshness approach, in which consumers may specify their particular requirements in terms of information freshness. This parameter will be interpreted by the Content Stores, which will consider it to determine whether or not they have the suitable information available. When the data with the desired freshness is not available in the cache, it will cause a Cache Miss and the request will be forwarded towards the information source or another entity able to satisfy the desired freshness. The freshness from the producer side must be kept to ensure the appropriate control over the generated information. However, based on the freshness being requested by the consumers, the producers may take a decision about the ideal value of freshness to be include in the Data packet.

The protection of systems against potential security threats (e.g., Denial of Service (DoS) attacks resulting from the systematic requests of low freshness values) should be considered when applying the new consumer driven freshness mechanism. Possible approaches to secure the proposed mechanism include limiting it by scope, using signed information in the Interest packets, etc. However, security issues are beyond the scope of the current paper.

B. *Implementation Details*

In implementing the proposed approach, we have included a new optional field in the Interest package for setting the necessary freshness for the information being requested. A new check step has been also added to the Content Stores for determining, based on the timestamp of the currently cached Data packet, whether the stored copy meets the freshness required by the consumer or not. If a cache miss is detected, the Content Store will forward the Interest packet towards the producer. This process will therefore be followed by all the Content Stores on the path to the source and, if none of them is able to satisfy the request, it will finally get to the source which will issue the new information. Moreover, as the information in the caches are updated whenever a new Data packet for the same content arrives, other potential consumers will be also benefited from this process.

A very simple freshness agreement between consumers and producers has also been considered. According to this agreement, any request involving a freshness value greater than the one currently provided by a Producer will lead to the immediate increase of the freshness requested until it reaches a top value defined by the Producer. This is now possible because the consumer is able to state the freshness value it needs and, as such, no problem will be originated if, in accordance to this agreement, the packet remains in the cache longer than expected.

IV. Experiments

In this section, we present our simulation results pursued in two directions: evaluation of the effects of the freshness parameter on the network performance and validation of the proposed freshness mechanism.

A. *Evaluation Goals*

The specific evaluation goals of this research work are focused on the assessment of the following research issues:

1) The impact of the freshness parameter included in Data packets and the size of the Content Stores (expressed as the ratio of the cache size and the total number of generated contents) on the reliability of data received by the consumers.
2) The influence of the above parameters on the network performance, in terms of cache hits and average number of combined hops of Interest and Data packets.
3) The improvement to the network performance introduced by the consumer driven freshness mechanism proposed in this work.

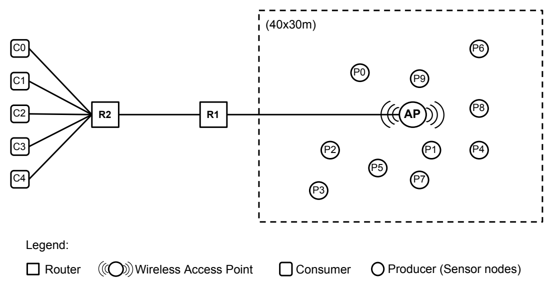


Fig. 1. Topology of the simulated scenarios

B. Setting up simulations

The ndnSim [23] simulation tool was selected for conducting the experiments in the present work. This simulation platform is based on the NS-3 network simulator framework and implements the basic components of a NDN network in a modular way. The ndnSIM includes a number of basic traffic generator applications and helper classes to simplify creation of simulation scenarios and tools to gather simulation statistics for measurement purposes.

Some modifications and extensions to the modules provided by the ndnSIM were required to ensure the development of simulations closer to the IoT concepts described in previous sections, as well as to apply the proposed consumer freshness mechanism. The implemented modifications and extensions are mainly referred to the following modules: *Consumer* - it will always ask for the same content name and it will also be able to specify a desired freshness; *Content Store* - it will always check whether or not a given stored Data packet satisfies the consumer desired freshness; *Interest packet* - a new optional freshness field was included; *Producer* - it will be able to change the freshness of the Data packet in accordance to the described simple freshness agreement algorithm; *Wire* - it will take into account the freshness parameter in the serialization and deserialization of Interest packets.

The simulated scenarios are based in a topology composed by ten producers and five consumers as shown in Figure 1. The producer nodes are WiFi stations connected to an Access Point in infrastructure mode. The Access Point is connected to a router, which in its turn is connected to the router associated to the consumer nodes. The producers are randomly allocated within a 40x30 meters rectangle centered on the Access Point. WiFi stations were set to follow a random walk movement within the boundaries of such a rectangle. The Three Log Distance and Nakagami propagation loss models provided by NS-3 were selected to take into account the losses due to variations on distance as well as the fast fading associated to wireless channels.

C. Scenarios

Two different scenarios are applied, especially designed to facilitate the achievement of our research goals. In both cases, consumers were set with no cache to avoid content from being supplied by their internal cache. In the same way, consumer applications were set not to use sequence numbers but only the desired content name. In all the cases the LRU (Least Recently Used) replacement policy was considered. Ten runs were considered in order to be able to determine a confidence interval for the obtained results.

1) Scenario 1: This scenario aims at addressing the first two research issues. It implements a case where all the consumers have the same information freshness requirements. Consumers' applications will start and finish requesting content at some random instant chosen uniformly within the intervals $[0; 15]$ and $[45; 60]$ seconds respectively. Each consumer will request sensed data from all the producers at a rate of one Interest packet per second with random requesting times uniformly distributed. Freshness and Content Store size are the parameters to be varied among simulations.

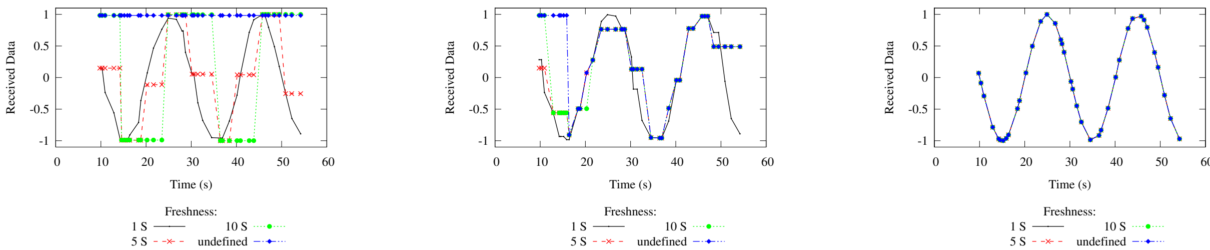
2) Scenario 2: A second scenario was conceived for addressing the third research issue. It implements a case where consumers can be divided into two groups with different information freshness requirements. Consequently, it will involve two different requirements from the network. The percentage of active time for consumers with more strict requirements will be considered to be lower. Four of the consumers, requiring a higher freshness value, will start and finish requesting content at some random instant, chosen, as before, uniformly within the intervals $[0; 15]$ and $[45; 60]$ seconds respectively. However, in this scenario each of these consumer nodes will now request sensed data to all the producers at a rate of one Interest packet every four seconds with random requesting times uniformly distributed. These nodes will have a higher freshness requirements, with a tolerance for data freshness of 4s. The fifth consumer will simulate a more strict freshness requirement, with it being active by a fraction of the operational time of the other four consumers, represented by the "α" parameter. This fifth node will be considered to have a more intensive request frequency of one Interest per second and a tolerance for a data freshness of 1s. The freshness of the producers was set to 1s, to ensure the adequacy of the data received by the more restrictive node. The maximum freshness allowed by the producer was set to 10s. The "α" factor and the Content Store size are the parameters to be varied varied among simulations.

D. Results

For simulation purposes, it was assumed that the data sensed by the producers and being received the consumers have a sinusoidal shape characterized by a unitary amplitude and a period of 20s.

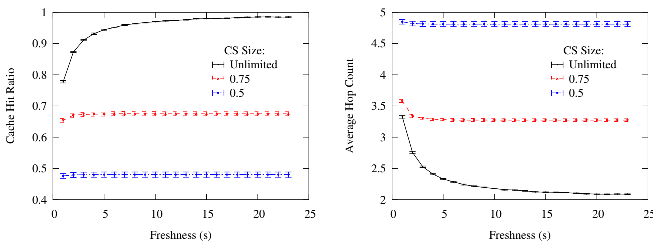
Simulation scenario 1 was applied to address the first research issue of this work. Figure 2 shows the data as received by consumer nodes for 3 different decreasing content store sizes, applying the same 4 selected different values of freshness. Content Store sizes vary from a 10% (0.1) store capacity to an unlimited one. Freshness values range from the requesting Interest packet period (1 second) to its complete absence.

Simulation scenario 1 was also applied to address the second research issue of this work. Figures 3(a) and 3(b) show, respectively, the cache hit ratio and average number of hops as a function of freshness for different Content Store sizes. Figures also show the confidence interval of data calculated on the basis of the result of the different runs. Results obtained for Content Store sizes with 10% store capacity are not shown in



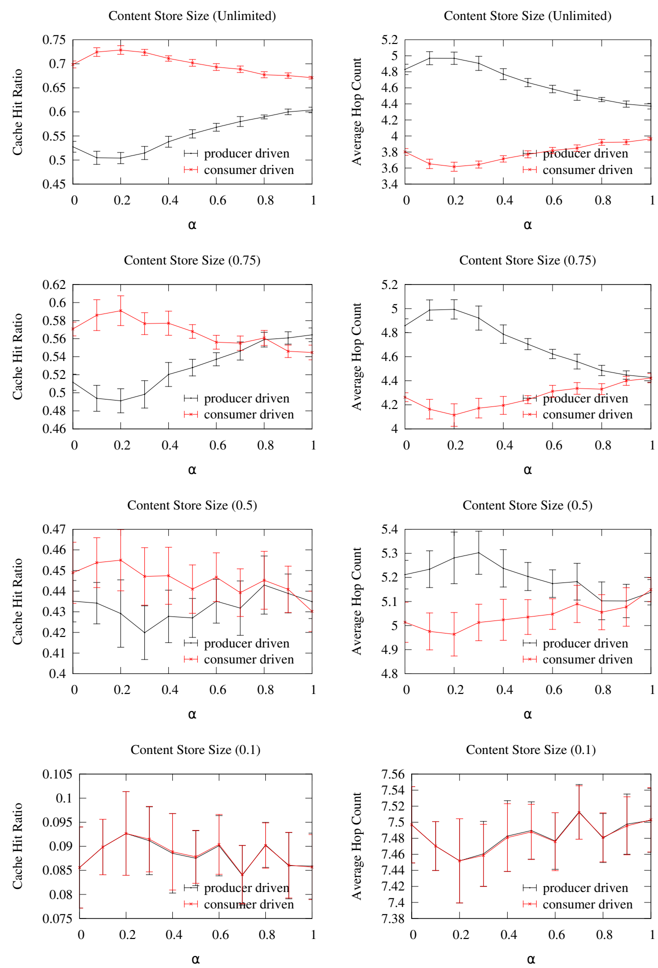
(a) Content Store Size (unlimited) (b) Content Store Size (0.75) (c) Content Store Size (0.1)

Fig. 2. Received data for different freshnesses and content store sizes



(a) Cache Hit Ratio (b) Average Numbers of Hops

Fig. 3. Simulation results for different values of freshness and content store sizes



(a) Cache Hit Ratio (b) Average Numbers of Hops

Fig. 4. Simulation results for different values of "α" and content store sizes for both producer driven and consumer driven freshness mechanisms

this paper, as they exhibit almost constant values regardless of the freshness value applied. (cache hit ratio = 0.1 and average number of hops = 7.4 of a possible maximum of 8)

Simulation scenario 2 was applied to address the third research issue of this work. In evaluating the effect of the proposed consumer driven information freshness approach on the performance of the network, simulations were firstly developed using consumer freshness mechanism and afterwards repeated using the simple freshness mechanism driven by the producers. Figures 4(a) and 4(b) show the cache hit ratio and average number of hops as a function of "α" (i.e., the ratio among the operational time of the more restrictive and less restrictive in freshness consumers) and the Content Store sizes. Figures also show the confidence interval of data calculated on the basis of the result of the different runs and are organized in rows, following 4 different decreasing content store sizes.

E. Discussion

Results from simulation scenario 1 have confirmed the benefits derived from the adoption of a freshness parameter in terms of the reliability of data received by the consumers. Figures 2(a) and 2(b) clearly confirm that lower freshness values lead to better data quality, because the system will need to drop the stored content more frequently to satisfy the freshness established by the producers. Figure 2(c) shows that the freshness parameter loses importance as the cache capacity gets more limited, because the cache will be forced to replace its content more frequently. From Figures 2(a)-2(c) it can be derived that, when the freshness parameter is not defined, the quality of the data being received entirely depends on how frequent the cache will be forced to execute a content replacement. Simulation results clearly highlighted the importance of the appropriate selection of the freshness parameter in accordance to the information being sensed and the requirements of the application.

Further application of the simulation scenario 1 demonstrated that some restriction should apply in adopting low values of freshness. Figure 3 demonstrates that low values of freshness affect the performance of the network in terms of cache hits and average number of hops required for a given application request to be fulfilled. This is an important fact that needs to be considered in scenarios involving applications with different freshness requirements, where in order to ensure the adequate work of the system, the producer must set the freshness parameter to the minimum value among those involved in the application.

The impact of the new proposed consumer driven freshness mechanism in addressing this issue is evaluated using the simulation scenario 2. The results in Figures 4(a) and 4(b) determine that the better performances of the network result from the use of the proposed consumer freshness mechanism. The biggest improvements are achieved when the Consumer with the more strict freshness requirement was active 20% of the time the rest of the consumers were active. Once again, in very limited content store scenarios, both mechanisms lose relevance as almost no caching can be performed.

V. Conclusions

This paper provides a summary of the main efforts of the research community in integrating the ICN and IoT concepts. It also presents a simulation study that highlights the convenience of controlling the information freshness in IoT scenarios. The available CCN mechanism for freshness control was examined in detail and a new consumer driven information freshness approach for CCN was proposed. Two simulation scenarios were designed and developed to characterize the CCN mechanism for freshness control and to evaluate the new proposed mechanism. While ensuring the data quality in environments featuring consumers with different freshness requirements, the new proposed approach showed to be a viable solution to reduce the negative effects of the freshness on the network performance. The obtained results have indicated that, jointly with naming, freshness results as a key issue when applying CCN to IoT environments.

The achieved results have emphasized the need for further evaluating the impact of information freshness mechanisms in IoT scenarios. Specific already identified areas for future work include: i) to extend this study to real sensors and to assess its significance not only for the network but also for the constrained device itself, mainly in terms of energy efficiency; ii) to design and evaluate more complex algorithms for the freshness agreement procedure, and iii) to extend the scope of this work to different cache replacement and decision policies and to study their impact in the studied IoT scenarios.

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