An Energy Efficient and Software-Defined Information-Centric Networking Approach to Consumer Mobility

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ABSTRACT

Smart mobility embraces many services that require the exchange of huge amount of data between mobile consumers (e.g., vehicles, drones, smartphones) and fixed producers (e.g., cloud servers). Information Centric Networking emerged more than one decade ago as a suitable approach to build the Future Internet, offering flexible communication primitives for data exchange and native support to mobility. Unfortunately, baseline schemes do not take care of stale forwarding information generated into the core network because of consumer mobility and, as a consequence, it leads to an important waste of bandwidth and a higher energy consumption. An SDN-aided Information-Centric Networking approach has been recently formulated by the same authors of this contribution as a valid solution for the aforementioned issue. This paper further extends these promising research results by evaluating the impact of the amount of energy consumed by intermediary routers. The conducted tests demonstrate the proposed solution effectiveness through computer simulations, by considering different network, mobility, and application scenarios.

Keywords: SDN, ICN, consumer mobility, energy saving.

1. INTRODUCTION

Information-Centric Networking (ICN) represents a consolidated communication paradigm for the Future Internet. By proposing a data-centric usage of the entire network infrastructure, it offers multiple advantages, including a rapid, reliable, and effective dissemination of self-secure contents, an optimized and energy-efficient use of network resources through name-based routing strategies and intelligent caching policies, simplified support for user mobility and greater resilience of the network infrastructure to system failures [1]. In general, the ICN communication architecture can be conceived as an overlay network, directly installed on the transport network (datalink, optical network) or on top of the IP protocol. The Named-Data Networking (NDN) project is an effective and open-source ICN implementation, studied and used all over the world [1].

Since name-based routing strategies do not entail information on the physical location of contents, NDN natively offers the possibility to manage data exchange in mobility conditions. Unfortunately, baseline NDN schemes do not take care of stale forwarding information generated in the core network because of consumer mobility, causing a significant waste of bandwidth and energy [2]. Consumers establish multi-hop communication path with remote producers, asking for content they're interested in. When a mobile consumer changes its network attachment point, a new path is established and the path established before the handover, namely stale path, remains still active. Inevitably, contents will be delivered across all active paths, including stale ones, wasting precious network resources and energy.

Recent works in literature speculated about the use of Software-Defined Networking (SDN) to increase and/or improve the functionalities of NDN [3]. In fact, NDN greatly benefits from the improved security, view, and control over distributed elements offered by SDN. The SDN paradigm implements network logic through a Software-Defined network Controller (SDC), which holds information on all network devices and is able to regulate forwarding and caching rules dynamically [4]. The works presented in [5-8] design novel protocols based on NDN and SDN to manage consumers in mobility scenarios. Nevertheless, they do not consider the impact of stale paths on the network, nor they evaluate the energy consumption in mobility conditions.

An SDN-aided Information-Centric Networking approach has been recently formulated by the same authors of this contribution as a valid solution for the aforementioned issue [2]. This paper further extends these promising research results by evaluating the impact of the amount of energy consumed by intermediary routers.

The rest of the work is organized as in what follows. Section 2 presents the conceived protocol architecture and minutely describes related mechanisms. Section 3 presents methods and parameters chosen for the numerical analysis, along with the corresponding results. Finally, Section 4 draws the conclusions and hints at future research.

2. THE PROTOCOL ARCHITECTURE

Fig.1 shows the reference architecture proposed in this work. It includes network attachment points, an ICN core network (i.e., transport network), a centralized SDC, a fixed producer, and a mobile consumer. Network attachment points are deployed throughout the network to offer connectivity by several radio-access technologies (like Wi-Fi, 5G, LTE, and others). NDN is considered implemented as an overlay over IP.
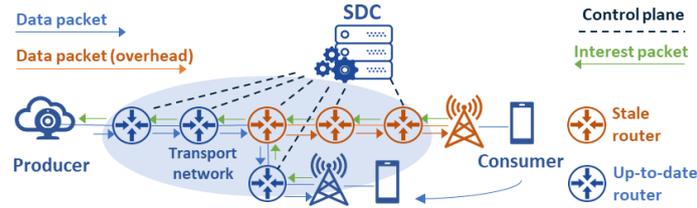
Figure 1. Reference network architecture

Contents in NDN are identified by a unique name, which affects forwarding operations in the network. The communication follows a receiver-driven scheme: the consumer requests a content by issuing an Interest packet; the network forwards back the requested content through a Data packet. Efficient data dissemination is achieved by means of network caching, content requests aggregation, and routing by name. These mechanisms require three data structures in each NDN router, that are: Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB). The CS of intermediate routers stores cached contents. PIT keeps track of the received Interest packets and the network interfaces they came from. This information is used to forward Data packets back to consumers across the same path of the request. PIT tables are also used to aggregate requests for the same contents. Finally, the FIB table implements forwarding rules, based on the Longest Prefix Matching criteria. FIB rules are created with a routing protocol like the Named-data Link State Routing (NLSR) protocol [9], while rules in PIT tables are generated on consumer demand when an Interest packet is received. Unfortunately, after the handover, the consumer establishes a new multi-hop communication path with the producer, while the previous one, the stale path, remains still active. Inevitably, contents are delivered also on stale paths and generate an unpleasant communication overhead on the data plane, as shown in Fig. 1. The SDC knows the network topology and communicates in-band with other network nodes. The SDC is also able to update forwarding information in NDN routers. The producer generates contents in real-time, hence no copy of these is stored in CS throughout the network before the consumer requests. Generated contents are identified by a unique content name, which includes a topic name and a numerical id. Finally, the mobile consumer requests a content of interest each time it attaches to a network attachment point.

The conceived protocol architecture comprises data exchange, handover, re-synchronization, and neighbour inspection functionalities:

a) **Data exchange:** it starts when the consumer establishes a connection with a network attachment point and starts to issue its requests by following a request-response scheme. First, the consumer sends an Interest packet for a content it is interested in. Then, each time one of the requested contents is received, the consumer sends a new request.

b) **Handover:** it is executed when the consumer detaches from the network. The network attachment point that detected the handover sends a Handover Initiation message to the SDC, announcing the consumer mobility and conveying the name of the latest, and not yet received, content requested by the consumer.

c) **Re-synchronization:** when the consumer attaches to a new attachment point, the latter requests the latest id available for the topic name the consumer is interested in. This way, the consumer knows the latest numerical id associated to its topic of interest and is able to retrieve all contents missed during the handover. Then, the new attachment point sends a Handover Completion message to the SDC, notifying the new location of the consumer.

d) **Neighbour inspection:** when the SDC receives the Handover Completion message, it sends a message to the network attachment point which started the handover functionality, communicating the content name of the latest content requested by the consumer and the interface between the consumer and the inspected NDN router. The inspected NDN router is now able to compare the information received with its PIT table. It selects the PIT entries which match the content name and the face received, and acts in two ways: 1) it deletes the entries displaying only the interface related to the consumer; 2) it removes the interface related to the consumer in the entries where other interfaces are exposed. Then, if any entry was deleted, the inspected NDN router answers to the SDC with the content name corresponding to the deleted entry. The SDC will then interact in the same way with the neighbours of the router which answered at the previous step. Among all the inspected neighbours, only one of the NDN routers forwarded the Interest packet and, therefore, will answer to the SDC. Again, the SDC will interact with the neighbours of the NDN router which answered. The process continues until the SDC receives no answers, which means all the stale information have been removed.

In the conceived protocol architecture, control information is carried by information-centric primitives with content name set to *ndn://[protocol]/[entity-name]/[topic-name]/[options]*. More in detail, control information is carried both by the content name and the requested content itself.

3. NUMERICAL ANALYSIS

According to [10], the energy consumed by an NDN router implemented on a PC-based hardware platform depends on CPU load, memory access rate, IP packet forwarding rate, and fixed costs. CPU load, memory access rate and IP packet forwarding rate dare related to the load on CPUs, memories, and network interface cards, respectively. Finally, fixed costs include power consumed by the NDN routers when their hardware components are idle. Considering a high-density urban scenario, it can be assumed all NDN routers are in an active state and that CPUs of NDN routers work in a high load condition. In this condition, the contribution due to the packet forwarding of real-time generated contents to the CPU load and memory access rate is negligible. Moreover, considering that fixed costs do not change between the proposed architecture and the ICN core network, the conducted numerical analysis focuses on the amount of power consumed by network interface cards.

As discussed in [10], the power consumed at each network interface card to forward a single IP packet is ψ=12.6 µJ/packet and the maximum size of IP packets is set to 1500 B. Considering Interest and Data packets' header sizes are set according to NDN specifications in [1], each Interest and control related NDN message can be sent as payload of a single IP packet, while bigger Data packets must be fragmented over multiple IP packets.

This work considered the average time interval between the generation of consecutive contents, namely T_D, ranging from 0.1 s to 10000 s and content sizes equal to 5 kB, 500 kB and 50 MB. These values are chosen to cope with bursty applications, which could heavily harm network performance. The conducted simulations considered a 10 km x 10 km urban area, two different average cell radius of network attachment points r equal to 50 m and 150 m, and two different consumer speed values, being 3 km/h and 30 km/h. Network attachment points are connected to a core network composed by N nodes, where N is equal to 1415 and 12732 for r=150 m and r=50 m, respectively. Those nodes are connected according to scale-free networks theory, where nodes are distributed with a power law factor γ=3 and each new node is connected to two previously existing nodes, following the preferential attachment law [11]. Several topologies were generated with these characteristics with the Representative Internet Topology gEnerator (BRITE). Then, random positions are considered for the consumer, producer, and SDC and mobility is simulated with a MATLAB script. The outcome of conducted simulations is averaged on 30000 realizations.

Fig. 2 reports the average daily energy consumption per consumer due to the forwarding of control and unuseful data packets throughout the network, both in case of the proposed architecture and the baseline NDN approach.
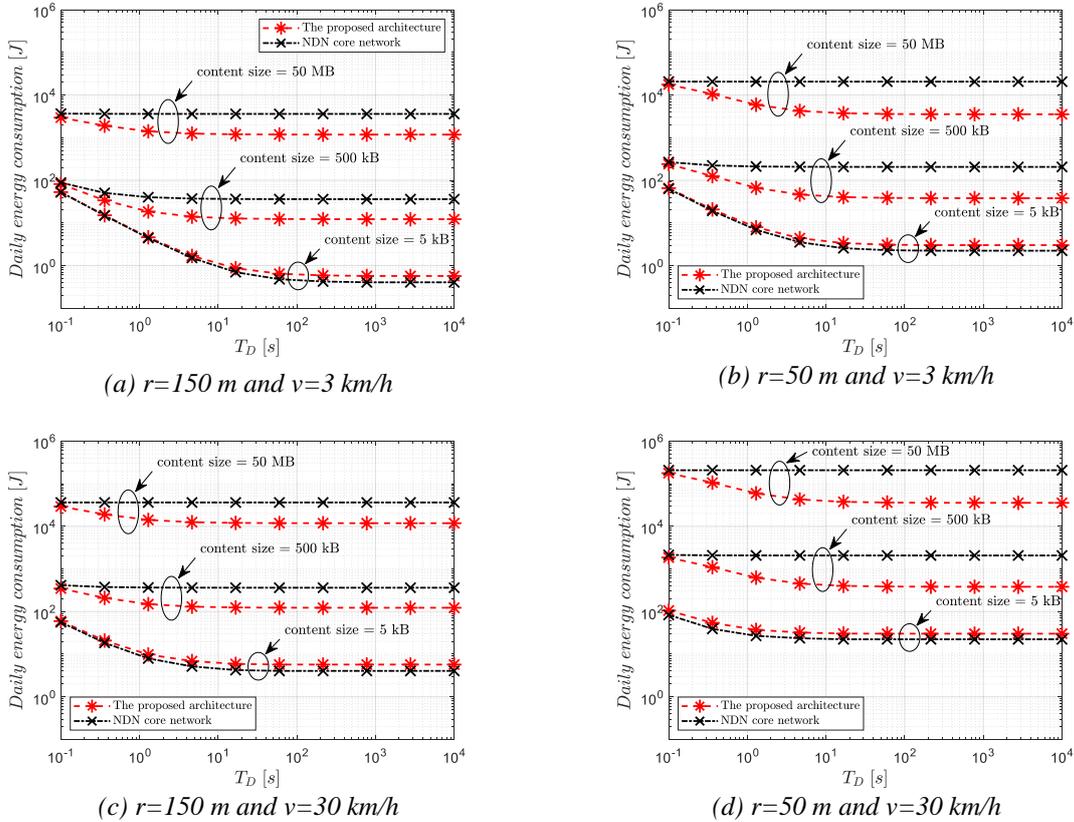

Figure 2. Daily energy consumption per consumer as a function of network, mobility, and application settings.

It is clear how the energy consumption increases with the average consumer speed and decreases with average cell radius. This is due to the mobile consumer changing cell more often and causing handover-related message

exchanges to occur more frequently. Concurrently, the energy consumption decreases with the average time interval between the generation of two consecutive contents and increases with the content size. In both cases, a higher number of IP packets are sent, therefore a higher amount of energy is spent in network interface cards throughout the network. Fig. 2 demonstrates that the conceived protocol is able effectively reduce the amount of energy consumed in case of bigger content sizes, that are 500 kB and 50 MB, and works even better when the average time interval between the generation of two consecutive contents increases.

CONCLUSIONS

This work evaluated the impact of the energy consumed by intermediary routers of an SDN-aided Information-Centric Networking approach, designed by the same authors of this contribution, and compared the outcome to the baseline NDN core network. The conducted simulations involved different network, mobility and application settings. The results demonstrated the effectiveness of the proposed solution in case of bigger content sizes and larger average time intervals between the generation of consecutive contents. Future activities will extend and optimize the protocol architecture in case of multiple mobile consumers and multiple Software-Defined Networking controllers.

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