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Toward Information-Centric Software-Defined Cellular Networks

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***Abstract*—The concept of software-defined networking (SDN) is able to offer important advantages over the traditional communication paradigms. This is achieved by decoupling the decision-making process from the underlying network infrastructure that forwards the traffic. Recently, there have been efforts in applying the SDN approach to wireless and cellular networks. In fact, SDN is considered as one of the key enablers for future 5G communication networks. Information-centric networking (ICN) is another emerging communication paradigm that has been proposed to improve the content delivery efficiency compared to the traditional host-centric communication protocols. ICN decouples the data from their location, application, and means of transportation. This feature makes ICN particularly suitable for efficient dissemination of large volumes of data, especially in highly dynamic and heterogeneous mobile environments. In this work, we consider an SDN-enabled cellular network and propose an ICN protocol to ensure fast and efficient content dissemination to mobile users. The proposed protocol has been evaluated by means of computer simulations for the use case of a live video streaming service. Our experimental results show significant improvements in terms of response times over the current long-term evolution (LTE) networks.**

Keywords—Software-defined networking; information-centric networking; cellular network.

I. Introduction

The appearance of end user devices with advanced capabilities, such as smartphones and tablet computers, has led to the emergence of novel services and networking technologies. According to CISCO's report, almost half a billion mobile devices and connections were added in 2016 [1]. At the same time, network and content providers experience a dramatic traffic growth. According to forecasts, the mobile traffic will increase in the order of 1,000 times in the next decade [2]. These changes drive the development of future 5G networks, which are expected to offer ubiquitous connectivity, fast response times, very low latency, and high data rates by creating the illusion of infinite network capacity [3]–[5].

One of the key enablers for future 5G communication networks is the software-defined networking (SDN) concept. SDN is currently at its rise due to a number of important advantages it offers over the traditional communication paradigms. Some of the advantages include network reconfigurability, greater flexibility in terms of new services deployment and management, and more efficient use of network resources. SDN architectures decouple the decision-making and control functions from the traffic forwarding functions operated by the underlying network infrastructure. This enables network control and management to become directly programmable and the underlying infrastructure to be abstracted from applications and network services [6], [7].

SDN was born with the original purpose of dealing with wired networks. However, very soon it became apparent that SDN can bring great advantages in the wireless world too. Designers of future 5G architectures realized that the separation of user and control planes via SDN will improve the network flexibility, reconfigurability, and programmability, as well as will allow multi-tenancy and efficient multi-service support [8]–[10]. Although it was anticipated, since it has been a big challenge to apply SDN concepts in wireless and cellular environments, some recent research efforts show very promising results toward this direction [11]–[15].

Information-centric networking (ICN) [16], [17] is another emerging communication paradigm that has been proposed to improve the content delivery efficiency compared to the traditional host-centric networking (HCN) protocols. HCN focuses on *who* to communicate with. Content is obtained by contacting specified named hosts. On the other hand, ICN focuses on *what* to communicate. Hence, ICN provides native network primitives for content retrieval by directly naming and operating on information objects. Some of the advantages of ICN over HCN include: i) native support for multicast and anycast; ii) good support for content consumer/provider mobility [18]; and iii) good support for in-network content caching and multi-source content delivery [19]. ICN decouples the information objects from their location, application, and means of transportation. This feature makes ICN particularly suitable for efficient dissemination of large volumes of data, especially in highly dynamic and heterogeneous mobile environments [20].

In our previous work [21] we proposed an SDN-based cellular architecture and evaluated the caching function in terms of network traffic savings. In this work, we implement and evaluate two other important network functions, namely the *request resolution function* and the *content routing function*. In particular, we consider an SDN-enabled cellular network and propose an information-centric SDN (IC-SDN) protocol for locating and disseminating content to mobile users (MUs). We use as a springboard the current long term evolution (LTE) architecture and extend it with SDN controllers at both the mobile core network (MCN) and the radio access network (RAN). Next, we design an ICN-based protocol that: i) enables the SDN controllers to communicate with each other and to configure the forwarding elements; ii) allows fast and efficient search of appropriate content server; iii) enables the forwarding elements to efficiently disseminate content to one or more destinations; and iv) achieves fast response times while introducing little signaling overhead.

The remaining of the paper is organized as follows. In Section II, we briefly present the related work on the applicability of ICN concepts in cellular networks. In Section III, we present our considered SDN based cellular architecture and introduce the necessary terminology. In Section IV, we present the applicability framework of ICN and SDN principles in cellular networks; benefits over the current LTE networks are also discussed. In Section V, we propose an IC-SDN protocol for cellular networks focusing on the request resolution and content routing functions. In Section VI, we compare the proposed protocol with the current LTE approach in terms of response times of a live video streaming service. We conclude and discuss our future work in Section VII. Also, in Table I we present the list of abbreviations used in this paper.

TABLE I. LIST OF ABBREVIATIONS

CCRF	Core Content Routing Function
C-ID	Chunk Identifier
CRRF	Core Request Resolution Function
CSC	Core SDN Controller
DNS	Domain Name System
HCN	Host Centric Networking
HD	High Definition
HTTP	Hypertext Transfer Protocol
ICN	Information Centric Networking
IC-SDN	Information Centric Software Defined Networking
IP	Internet Protocol
LCCF	Local Content Caching Function
LCRF	Local Content Routing Function
LRRF	Local Request Resolution Function
LSC	Local SDN Controller
LTE	Long-Term Evolution
MBS	Macro-cell Base Station
MCN	Mobile Core Network
MNO	Mobile Network Operator
MU	Mobile User
O-ID	Object Identifier
P-GW	Packet Data Network Gateway
QoE	Quality of Experience
RAN	Radio Access Network
SBS	Small-cell Base Station
SDN	Software-Defined Networking
S-GW	Serving Gateway

II. RELATED WORK

In this section, we present recent works that apply ICN concepts in next-generation cellular networks [22]–[26]. In most of the cases, the presented experimental results indicate significant network performance improvements compared to traditional HCN approaches.

In [22], the feasibility of applying the ICN principles in LTE networks has been investigated. The focus is on improving the quality-of-experience (QoE) of MUs by deploying caches at the RAN. Different LTE modulation and channel bandwidth parameters have been tested. The proposed approach in most of the cases results in lower content access delays and reduces the traffic at the MCN. Finally, performance comparisons of ICN caching with the traditional HTTP caching have been performed. The derived results indicate greater scalability and flexibility of ICN based solutions.

In [23], the benefits of network virtualization and ICN caching have been investigated in the context of device-to-device communications. The authors formulate the virtual resource allocation and caching strategies as a joint optimization problem. Particular emphasis is given on reducing the computational complexity and the signaling overhead. As the experimental results suggest, the proposed distributed algorithm can achieve a fast convergence rate even without relying on the exchange of channel-state information.

In [24], a peer-to-peer mobile application for live video streaming is presented. The application exploits the main functionalities of ICN, such as named routing, in-network caching, and multicasting. This enables neighboring MUs and Wi-Fi users to collaborate by utilizing the Wi-Fi network. Different user collaboration strategies have been investigated and the experimental results show improved performance of the video streaming service.

In [25], ICN principles have been applied to enable scalable mobile backhauling. In particular, the in-network caching feature of ICN has been exploited to reduce the content delivery time and to achieve significant bandwidth savings compared to the traditional HCN solutions. This is based on a large set of traffic measurements that suggest that 50% of the HTTP traffic is cacheable. However, the caching performance optimization has not been further investigated.

In [26], the optimization problem of wireless network virtualization and ICN has been studied. The aim is to enhance the QoE of the MUs and to reduce the infrastructure costs for the mobile operators. This is achieved by solving the joint optimization problem of virtual resource allocation and in-network caching. Extensive simulation experiments show significant backhaul traffic savings and reduced content delivery times.

We observe that most of the aforementioned works on cellular ICN concentrate on the caching function only, for latency reduction and traffic servings. On the other hand, little work has been done to investigate the possibility of ICN-SDN co-design and to evaluate its benefits in the context of cellular networks. In this work, we try to fill in this gap.

III. SDN-BASED CELLULAR ARCHITECTURE

In this section we briefly describe our considered SDN-based cellular network architecture. Herein we focus only on the network elements and functions that are of interest for this particular study. The interested reader may refer to [21] for a more detailed description of the architecture. A simplified version of our considered cellular architecture for this study is depicted in Fig. 1. The cellular network consists of two main parts, the RAN and the MCN, which are described below.

A. Radio Access Network

At the RAN level, macro-cell base stations (MBSs) are grouped into clusters and each cluster is controlled by a local SDN controller (LSC). Our aim is to enhance the SDN controllers with ICN features. This is done in Sections IV and V, below. Other network elements at the RAN are: small-cell base stations (SBSs) and MUs. The LSC is a control plane entity and could be physically collocated with one of the

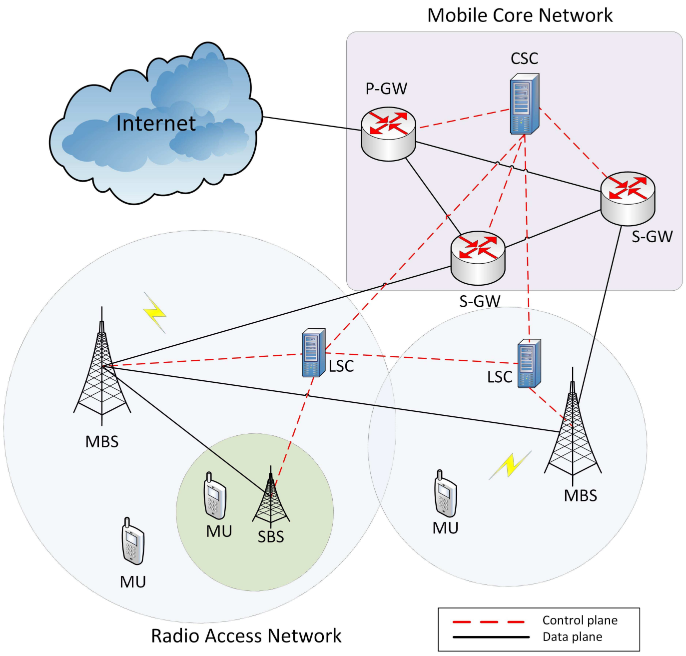


Fig. 1. The considered SDN-based cellular architecture. A core SDN controller (CSC) operates at the mobile core network (MCN) level. A set of coordinated local SDN controllers (LSCs) has been deployed at the radio access network (RAN) level.

MBSs. On the other hand, the other three elements (i.e., MBS, SBS, and MU) operate in the data plane and are controlled by the LSC.

The LSC is the first point of contact for a MU that wishes to initiate a new communication service. The request for a new service is handled by the local request resolution function (LRRF) of the LSC. The LRRF is responsible for locating an appropriate content server within the cluster or, if no server is found, for forwarding the request to the MCN. Once the content server has been identified and located, the local content routing function (LCRF) of the LSC is responsible for determining the appropriate delivery path from the server towards the requestor and for configuring the forwarding tables of all in-path forwarding elements.

B. Mobile Core Network

The main network entities at the MCN level are: core SDN controllers (CSCs), packet data network gateways (P-GWs), and serving gateways (S-GWs). A CSC operates at the control plane, whereas the two other entities operate at the data plane.

In this work we focus on two main functions of the CSC, namely the core request resolution function (CRRF) and the core content routing function (CCRF). The CRRF is responsible for identifying and locating appropriate servers at the MCN and inter-cluster levels. That is, the CRRF deals with the unresolved requests coming from the RAN (i.e, from the LRRF). Once an appropriate content server has been located, the CCRF is responsible for constructing the delivery path from the server towards the requestor at the MCN and inter-cluster levels. The role of P-GWs and S-GWs is similar to role of homonymous entities in LTE networks, but is restricted to data plane only (similarly to an OpenFlow switch [27]). A P-GW is used to access external IP networks, whereas a S-GW is used to access the RAN.

IV. Applying Information-Centric Concepts in Software-Defined Cellular Networks

The key driver for the introduction and development of LTE networks was the need to enable IP-based communication with particular emphasis on multimedia services. Today, however, we evidence the appearance of novel services with very strict requirements in terms of end-to-end latencies and response times. Examples of such services are high-definition (HD) live video streaming, augmented reality applications, and tactile Internet [28], [29]. The strict requirements of these novel services cannot be successfully met by relying on the current LTE-based networks. Their fundamental limitations lie in their centralized mobility management and data forwarding, as well as in insufficient support for multiple co-existing radio access technologies [4].

The basic HCN model, as implemented in current LTE networks, is shown in Fig. 2. Arrows represent various control plane and data plane messages. Numerical labels above or below the arrows denote the ordering constraints. That is, the order in which the messages must be sent and received. For example, an arrow labeled (2) must be sent and received before an arrow labeled (3) can be sent. Consider now the scenario shown in Fig. 2. Assume that a MU wishes to start a HD live video streaming service at a remote content server. The first step is to obtain the server's IP address. The MU sends the *IP address request* message to the domain name system (DNS) server and the latter responds with the *IP address response* message. This process is commonly referred to as the *DNS lookup* and is depicted in Fig. 2 by arrows labeled (1) and (2). The DNS server can be physically located either at the MCN (as in the figure) or on an external site. Once the MU has the IP address of the remote server, the former can send the latter a *content request* message (e.g., an HTTP request) and can then start receiving the requested data. The request message will typically go via the MBS, S-GW, and P-GW, assuming that the server is located in an external network.

In Fig. 3 we show how the scenario described above can be realized using ICN principles. ICN-enabled live streaming applications have already made their appearance (e.g., [24], [30]). The expected benefits include a reduced response time in comparison with the paradigm depicted in Fig. 2. We make the assumption that the mobile network operator (MNO) has: i) implemented the relevant ICN functions (described in detail in Section V) at the involved network elements (i.e., MU, MBS, S-GW, and P-GW); and ii) introduced in its MCN a new network entity, an ICN-enabled CSC. Optionally, the MNO may also introduce a number of ICN-enabled LSCs at the RAN level (as shown in the figure). This would reduce the response times for delay-sensitive services even more. Note that we do not make any assumptions with regard to the external networks and servers. These can still operate according to the traditional HCN paradigm (e.g., IP based communication).

According to the approach depicted in Fig. 3, the process of starting a live video streaming service at a remote server is as follows. The MU sends a *content request* message (a green

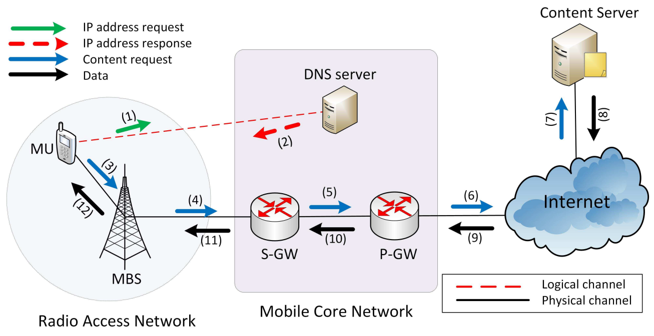


Fig. 2. Host-centric paradigm in current LTE networks. The network acts as a bit pipe without fine-grained control and flexibility.

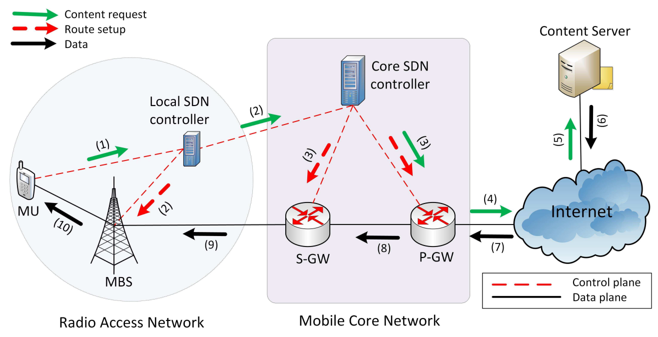


Fig. 3. Information-centric paradigm for SDN-based cellular networks - a motivating example. The network is content-aware and the SDN controllers can configure the content delivery paths in a dynamic manner.

arrow labeled (1)) to the LSC. The latter will either: i) satisfy the request (e.g., by forwarding the request to the appropriate server); or ii) will forward the request to the CSC and will notify the MBS via a *route setup* message that some content for the MU will start flowing soon. Below we describe the second case, which is also depicted in Fig. 3. Note that some arrows have the same labels. This means that the corresponding messages can be sent at the same time (although the reception times could vary). This is the case, for example, for the two red dashed arrows and one green solid arrow originating from the CSC and carrying the label (3).

In the scenario of Fig. 3, the CSC, upon receiving the *content request* message from the LSC, will perform the following actions: i) will forward the request toward the remote server (green arrows (3)-(5) in the figure); ii) will determine the MCN part of the delivery path toward the requesting MU (i.e., P-GW $\rightarrow$ S-GW $\rightarrow$ MBS in our scenario); and iii) will configure the forwarding tables of the involved in-path network elements, by sending the *route setup* messages (two red dashed arrows labeled (3)). Note that the rest of the delivery path, namely MBS $\rightarrow$ MU, has to be configured via the *route setup* message sent from the LSC to the MBS. This message is denoted by a red dashed arrow labeled (2). In Section V below, we provide more details of our proposed IC-SDN protocol intended to realize the SDN-based communication shown in Fig. 3.

By comparing the two approaches shown in Figs. 2 and 3, it is expected that the second approach can lead to reduced response times and smaller end-to-end latencies. This comes at the cost of an increased signaling load (a number of additional *route setup* messages needs to be sent). However, the introduced signaling overhead is expected to be very small. On the other hand, as our experimental results in Section VI show, the response time reduction is significant. Experimental evaluation of the signaling overhead has not been performed as part of the current work and is left as future work.

V. Control Plane Functions for Information-Centric Cellular Networks

In this section we describe our proposed IC-SDN protocol for cellular networks. We consider the cellular architecture of Section III and focus on two important network functions, namely the LRRF and the LCRF. Recall that these functions operate at the RAN level and are part of the LSC.

A. The local request resolution function (LRRF)

The LRRF is responsible for resolving the content requests originated from MUs. That is, the LRRF is aware of the content location within its cluster. If the requested content is not available within the cluster, the LRRF forwards the request to the CRRF located at the MCN as part of the CSC.

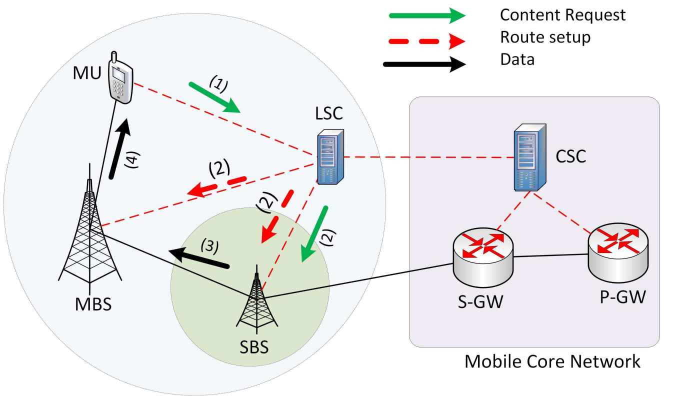
Below, with the aid of the simple example of Fig. 4, we describe the LRRF and its required data structures. The basic operation of the LRRF is supported by the *content table*, which stores the information about the available content within the cluster. According to the ICN principles, the content (e.g., a video file) is split into a number of chunks that can be stored and routed independently. For example, a 2 GB video file may be split into 500 chunks of 4 MB each. Each content object has a unique *object identifier* (O-ID). Also, each chunk of a particular object has a unique (within the object) *chunk identifier* (C-ID). As shown in the figure, the content table holds information about the location of specific chunks of an object within the cluster. The content table is populated by the local content caching function (LCCF). The latter has been described and evaluated in our previous work [21] and, therefore, will not be further discussed herein.

Consider the scenario where a MU wishes to initiate a video streaming service. When the user selects a video clip on his/her mobile browser, this triggers the issue of a *content request* message with a specific O-ID (associated with the chosen video clip) and a pre-defined range of C-IDs (e.g., the first 10 chunks). This message is sent to the LSC and is handled by the LRRF. Assume that O-ID="3" and C-ID="1-10". In the example of Fig. 4, the LRRF will consult its content table and will identify the SBS as the content source, where the content request message will be forwarded. After that, the control will pass to the LCRF that is described in the next subsection.

B. The local content routing function (LCRF)

The LCRF is responsible for: i) constructing the content delivery path/tree from a source to one or more MUs within the cluster; and ii) configuring the in-path forwarding elements via *route setup* messages.

Each forwarding element operates based on the current state of its *forwarding table*. The latter holds information about the next hop for given O-IDs and C-IDs. Entries in the forwarding table are created and deleted via *route setup* messages.



Content Table at LSC

Content ID	Chunk ID	Location
3	1-100	SBS
2	1-20	MBS
2	21-40	SBS
other	other	CSC

Forwarding Table at SBS

Content ID	Chunk ID	Next hop
5	1-50	S-GW
3	1-10	MBS

Forwarding Table at MBS

Content ID	Chunk ID	Next hop
5	1-50	SBS
3	1-10	MU

Fig. 4. Request resolution and content routing at the RAN - a simple example. The LSC receives the request from the MU, identifies the content source via the content table, and configures the forwarding tables of in-path elements via route setup messages.

In the example of Fig. 4, the involved in-path forwarding elements are the SBS and the MBS. Hence, the LCRF will send the following two route setup messages: *Route setup (O-ID="3"; C-ID="1-10"; Next-Hop="MBS")* and *Route setup (O-ID="3"; C-ID="1-10"; Next-Hop="MU")*, to the SBS and the MBS, respectively. The above messages will create new entries in the corresponding forwarding tables. Each entry will remain in the table for a specified time or until cleared via another *route setup* message.

VI. Evaluation

A. Preliminaries

In this section we compare our proposed IC-SDN protocol with the traditional HCN approach as implemented in current LTE networks. We focus on the evaluation of the response time when MUs request a HD live video streaming service. Our comparison is performed by means of computer simulations using a purpose-built ns3-based simulator [31]. Despite the availability of other simulators (e.g., OMNeT++, OPNET, NetSim, etc.), ns3 is currently one of the most popular network simulators in the research community. Besides being fast, stable, and well-supported, ns3 is also open-source and has a rich model library that includes popular networking technologies and protocols, including LTE networks. Furthermore, ns3 enables building customized simulation models with features very close to real systems and allows interoperability with existing models.

B. Simulation Models

Our developed simulation models for IC-SDN and LTE are in line with the descriptions in Sections IV and V. In particular, this refers to:

- network nodes: control plane entities (LSC and CSC), data plane entities (MU, MBS, S-GW, and P-GW), and a remote Content Server.
- network functions: content resolution (LRRF and CRRF), content routing (LCRF, CCRF), and caching (LCCF).
- protocol messages: content request, route setup, and data.
- data structures: content table and forwarding table.

Since the purpose of our comparison is at the architectural and functional level, we do not explicitly simulate the details of the radio propagation characteristics and the radio resource control. The simulated network topologies are similar to those depicted in Figs. 2 and 3, but are larger in order to evaluate more realistic scenarios. Specific details of two simulated scenarios are given below.

C. Simulation Scenarios and Results

In the first scenario we consider 4 clusters, each controlled by one LSC and supported by one MBS at the data plane. The LSC and MBS of each cluster are physically collocated. In each cluster 100 MUs generate video streaming requests at random times. One CSC has been placed at the MCN and the video streaming server is located outside the MCN. The server has 20 different video files available for request. With regard to the connection from the MCN to the remote server we consider the following three cases for both IC-SDN and LTE:

i fast connection: 1 Gbps with a delay of 10 ms.
ii medium-speed connection: 100 Mbps with a delay of 100 ms.
iii slow connection: 10 Mbps with a delay of 500 ms.

The backhaul connection (from each cluster to the MCN) is 10 Gbps with a delay of 10 ms. The radio access delay is variable: from 10 ms to 100 ms, as shown in Fig. 5. For our proposed approach we choose the simplest caching policy - the universal caching, where no intelligent caching decision-making is performed. This is done intentionally, so that our results are not affected by the caching algorithm in place. However, a number of proposed caching techniques could be used to improve the network performance even more [32]–[35].

In Fig. 5 we present the average response times of our proposed protocol and the current LTE approach. For the proposed approach we show results for the three different connection types to the remote server. For LTE we show the results for fast and medium-speed connections. We observe that the proposed approach can lead to significant reduction of the response time compared to what the current LTE networks are able to achieve. Even in the case where the connection to the streaming server is slow, the proposed approach achieves better results compared to the LTE network where a fast connection to the server is assumed.

In the second scenario we keep the radio access delay fixed to 20 ms and consider 400 MUs. We investigate the impact of the clustering algorithm on the response time. To this end, we

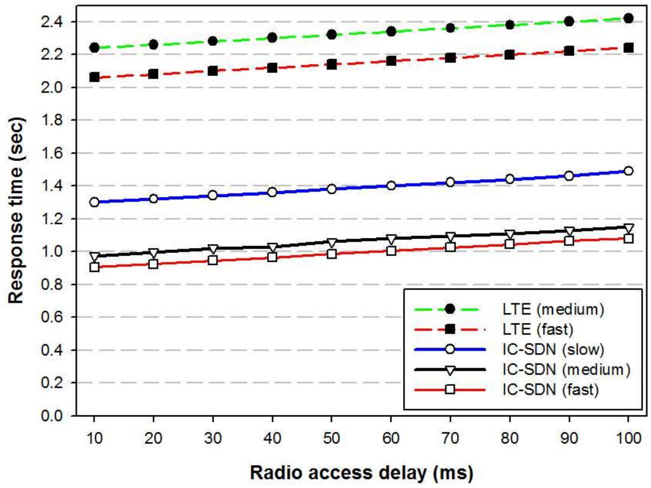


Fig. 5. Response time vs radio access delay for the proposed IC-SDN protocol and the LTE approach. Fast, medium-speed, and slow connections to the remote server have been investigated.

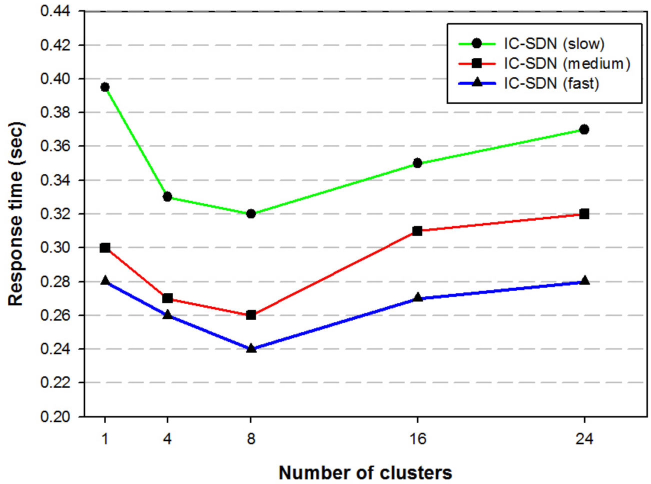


Fig. 6. Response time vs number of clusters for the proposed IC-SDN protocol. Fast, medium-speed, and slow connections to the remote server have been investigated.

vary the number of clusters (1, 4, 8, 16, and 24 clusters), as shown in the x-axis of Fig. 6. The number of the MUs among the clusters is uniform. That is, with 4 clusters we have 100 MUs/cluster, with 8 clusters we have 50 MUs/cluster, etc.

In Fig. 6, we observe that initially, when the number of clusters increases, the response time decreases until a topology with 8 clusters has been reached. After that, increasing the number of clusters will increase the response time. This suggests that the number of clusters, and hence the cluster size (i.e., the number of MUs per cluster), is an important optimization factor that needs further investigation and may impact the network performance.

Note that in the comparison of the proposed approach with LTE in the first scenario we have considered a sub-optimal number of clusters (i.e., 4 clusters). Hence, if a cluster optimization algorithm were used in the first scenario, the performance improvements over LTE would be even better. Finally, the introduced signaling overhead in terms of additional processing and traffic is negligible and is not presented.

VII. Conclusion and Future Work

In this paper, we present a novel ICN protocol for SDN based cellular networks. The proposed approach can be easily implemented on SDN controllers that operate at both RAN and MCN levels. We design and implement two important network functions, namely the request resolution function and the content routing function, according to the ICN paradigm. We evaluate our solution by means of computer simulations and perform a comparison with the traditional host-centric approach as implemented in the current LTE networks. Our extensive experimental results show significant reductions of response times when a large number of MUs request a high-definition video streaming service. We also study the impact of the cluster size on the network performance and identify optimal clustering for the chosen scenario. Further studies are required, however, to design an optimal clustering algorithm for the general case. In our future work we plan to design and evaluate an ICN based mobility management function. We also plan to extend our approach to support multi-source content delivery.

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