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LETTER

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Empowering 5G network softwarization through information centric networking

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Fifth-generation (5G) systems are designed as flexible and programmable multiservice networking and computing infrastructures, with improved throughput, latency, and reliability performance. In this paper, we discuss our view about the role of Information-Centric Networking (ICN) in 5G systems and present some architectural perspectives for the ICN-5G deployment. The proposed architecture relies on a *hybrid* approach, which makes the best of the *centralized* software-defined networking and the *distributed* ICN delivery mechanism to effectively suit the mobility of users, contents, and virtualized network/service functions. Its viability is showcased in a representative use case against a legacy non-ICN approach.

KEYWORDS
5G, information-centric networking, network function virtualization, software-defined networking

1 | INTRODUCTION

The encouraging results achieved by the Information-Centric Networking (ICN) research community have motivated standard and technical specification development organizations, such as the Third Generation Partnership Project (3GPP); International Telecommunication Union (ITU); and big industrial players like Intel, Cisco, and Huawei, to promote ICN as an enabler of fifth-generation (5G) networks.[1,2] Location-independent name-based communication, dynamic intelligent routing, and secured in-network content caching are the main ICN principles showcased in several wireline and wireless scenarios. Only a few studies, for example,[3] have targeted ICN deployments in cellular networks; this is mainly due to the operator ownership of the infrastructure, the consolidated deployment and standardization works of decades, the complexity of management of such networks, and the mature definition of control plane (CP) and user plane (UP) functions operated end to end by well-defined protocols built over IP.

The 5G architecture is taking shape with a different flavor compared to existing cellular networks: it is engineered with a natively *cloud-based* and *programmable core network*, enabled by the recent advancements in Network Function Virtualization (NFV) and Software-Defined Networking (SDN) technologies. In 5G systems, a traditional *network function* (*NF*), such as mobility management, will be no longer implemented in an operator-owned dedicated network node (ie, the Mobility Management Entity), but it will be deployed as a *virtualized* NF, instantiated where the network demands for it. The 5G network infrastructure will be in a close-knit relationship with the service delivery platforms, thus blurring the traditional distinction between network and service operators. Some *service functions* (*SF*), traditionally offered in the cloud of the service provider, can instead be offered by nodes in the edge of the mobile network operator (MNO), much closer to the end user in order to fulfill, for example, strict service latency requirements. 5G will implement a network of “virtual functions”, deployed *on-demand* and *on-the-fly* also by third parties and flexibly interconnected to meet diversified service requirements (eg, extremely high data rate, ultra-low latency, high user mobility, ultra-reliable communication, high scalability, and low cost[1]). Virtualized functions are *mobile* in nature, that is, they can migrate, being replicated and executed in different nodes; therefore, in a network of virtual functions, the NF/SF discovery and retrieval is a real challenge.

We believe that the ICN *name-based* forwarding and dynamic caching capabilities can help 5G to flexibly instantiate and access virtual NFs (eg, firewalling, packet inspection) and SFs (eg, video compression) to manipulate the data traffic in the UP and suit a specific use case. In this article, we target the shaping of ICN modules to make them *5G-ready,* including network softwarization "by design". We use Named Data Networking (NDN) as the reference ICN model. NDN is based on 2 types of *named* messages: *Interests* that request contents and *Data* that carry the content. We extend NDN beyond its original use for "named" content retrieval to also support named virtualized functions' code retrieval and local execution in the 5G ecosystem. As a result, based on their capabilities and enforced policies, NDN nodes will participate in the orchestration, retrieval, and execution of 5G virtual functions in a distributed manner, complementing the centralized (SDN-assisted) approach. This will improve the flexibility, agility, and reliability of the 5G network.

2 | 5G SYSTEMS AND ICN MATCHING FEATURES

5G is expected to realize a paradigm shift from today's 4G *network of entities* to a *network of (virtual) functions*. *Virtualized* NFs can be dynamically instantiated according to the NFV paradigm to meet specific operational needs. CP (eg, access control, mobility management) and UP (eg, per-user packet filtering, lawful interception) functions will be clearly decoupled, thus facilitating independent scaling and flexible service support. CP functions can be placed in a central site, which simplifies management and operation, especially if common to multiple flows, while some UP functions can be moved to the edge, closer to the user, to satisfy low-latency applications. Additionally, application-specific traffic, exchanged between the mobile network and an external data network (eg, a web server in a data center, a multimedia platform), can be manipulated by passing through a *chain* of given SFs. For example, the packets payload can be compressed to better fit the size of mobile devices' displays. Such SFs, instead of being embedded in purpose-built middleboxes, can be flexibly deployed as virtualized SFs, and MNOs will use these SFs to differentiate the offered services to their subscribers.

3GPP states[1] that 5G could benefit greatly by natively supporting ICN protocols. Here, we promote ICN[1] as a framework for both *named content retrieval and virtual function provisioning* in 5G. Germs of the idea of extending NDN to manage generic functions can be found in the literature. Named Function Networking in Reference [4] proposes that the network orchestrates the execution and delivery of named-based computation in a distributed manner. In Reference [5], the authors support in-network function execution by leveraging *unikernels*. Whereas the cited examples have been conceived as *stand-alone* solutions, our vision is *to natively embed* them into the 5G architecture, exploiting the fact that the main ICN features fit the 5G requirements, as highlighted below.

2.1 | Location-independent and contextual naming

ICN addresses contents (and functions) using hierarchically structured *names*, independent of the identity/location of the node generating/hosting them. As a result, the network can forward a named request in an *anycast* mode toward the most suited provider at that time, and consumer mobility is natively supported. Naming Data packets also allow ICN nodes to *recognize* the carried contents via their semantically meaningful names at the network layer, without the need for deep packet inspection (DPI) or delegation to upper layers. Contextual metadata that describe the desired content/function features can be carried as a name component without affecting the forwarding engine relying on the longest prefix matching rule.[(4,5)] In so doing, forwarding and caching strategies can be customized on a per-content/per-function basis.

2.2 | Access network agnosticism

Thanks to its connectionless transport, an ICN node with multiple interfaces can select the most convenient one at a given time on a per-packet basis or can transparently use multiple concurrent interfaces if a large bandwidth is required. This is particularly useful to 5G, which will include many heterogeneous access networks.

2.3 | Name-based (intelligent) forwarding

The ICN forwarding plane has the advantage (that comes for free) of recording given performance metrics (eg, throughput, round-trip time) for each data prefix. By using these soft-state parameters, the forwarding strategy can select the best outgoing interface(s) per packet and can fast react to short-term network churns. Such ICN capability is crucial in 5G systems, where the network topology and service demands may rapidly change (eg, due to node mobility, function migration) and affect the latency in the routing protocol convergence or the scalability of a centralized approach.

2.4 | In-network caching

Thanks to dynamic and opportunistic in-network caching, data retrieval can occur from sources closer to the consumers, for example, a Base Station, a nearby device, thus saving network resources in the core and backhaul links and reducing the retrieval

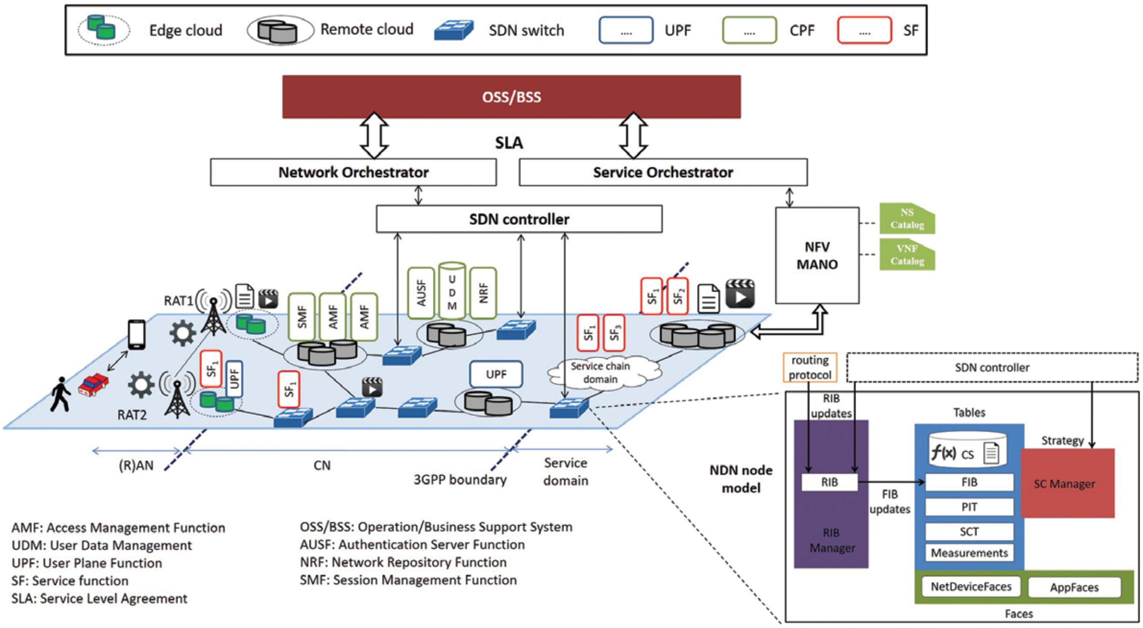

FIGURE 1 The proposed ICN-5G architecture and the overhauled NDN node model

latency. Moreover, a packet loss can be more easily recovered, with no need of retransmission from the original source. This would, in summary, result in an energy-efficient networking. Many ICN caching policies have been proposed, either to meet the content peculiarities (eg, freshness, popularity) or device capabilities—as surveyed in Reference [6]—which 5G could build upon.

2.5 | In-network security

Unlike the traditional Internet security that is an afterthought barely meeting the demands of current applications and users, ICN provides security at the network layer by signing all Named Data packets, including the signaling ones. Data signatures and publishers' information enable the data provenance determination; thus, the consumer trust in the Data is decoupled from how/where the Data is obtained. Applications can also control content access via encryption. This way, 5G will greatly benefit from ICN built-in security, which can secure applications, defend the infrastructure, and guarantee privacy.

3 | THE ICN-5G ARCHITECTURE

Our vision of an ICN-5G architecture aims to be aligned with ongoing 3GPP specifications so that ICN can natively be included in 5G. The envisioned ICN-5G architecture is illustrated in Figure 1. The bottom level shows: the 3GPP Radio Access Networks (RAN) and Core Network (CN) domains and related CP/UP functions for 5G (as specified in 3GPP TR 23.501) in the realm of the MNO, and the Service domain traditionally out of the 3GPP boundary. CP and UP functions over commodity hardware are interconnected through SDN-capable switches. SFs are natively hosted in cloud infrastructures and can be instantiated in (edge) network nodes. In line with the 5G architecture in Reference [7], the logical orchestration and control is based on the usage of SDN and NFV, and different orchestrators may be in charge of enforcing network/service policies and behaviors according to specific SLAs the MNO agrees with the vertical markets. According to our view, the NDN intelligent forwarding plane, with the (optional) SDN assistance, will instruct Interest packets to be routed toward the best provider hosting the requested named content/function code and/or locally executing a named virtual NF/SF. In this advocated ICN-5G context, an NDN provider could be an SDN-capable router in the transport network of the MNO, a remote server located in the cloud, a network node in the RAN or the edge, or even an end device. Such NDN-enabled nodes can self-adapt to the changing operative conditions, that is, their own capabilities, the MNO policies, and the network conditions and run the right NF/SF or shape the proper content/function code caching strategy.

3.1 | Function orchestration

We pursue a *hybrid* approach for an efficient and flexible resource and NF/SF orchestration, making the best of both (SDN-based) centralized and ICN-distributed solutions, as summarized in the key performance indicators (KPIs) in Table 1. In

TABLE 1 KPIs for the proposed hybrid approach against other networking solutions

KPI	Legacy ICN approach	Legacy SDN approach	Hybrid approach
Scalability	High	Medium	High
Latency	Low	High if the NFV catalogue/SDN controller need(s) to be contacted	Low
Signaling overhead	Low	High if the NFV catalogue/SDN controller need(s) to be contacted	Low
Reliability	Medium	High	High
Availability	High	Low in case of a single SDN controller	High

particular, 2 types of orchestrators account for the 2 main players (network and service providers) with neatly different scopes. The Network and the Service Orchestrators (top level of Figure 1) are, respectively, in charge of the NFs and SFs lifecycle.

The Management and Orchestration (MANO) capabilities of the ETSI NFV framework are responsible for tracking the set of services and mapping them to the corresponding function instances, both stored in dedicated catalogues. An SDN Controller then allocates the network resources over the paths interconnecting end nodes and intermediate nodes. It monitors the status of nodes, builds topology graphs, and injects forwarding rules for long-term operations.

According to the hybrid approach, this global orchestration can be occasionally complemented by *autonomous* decisions *locally* taken by ICN-enabled nodes. If, for instance, a given NF/SF is to be executed on a specific traffic flow, the centralized solution would require asking the corresponding Network/Service Orchestrator for a lookup in the catalogue and, subsequently, the SDN Controller to set up a path for the traffic flow toward the identified function. In contrast, ICN-capable nodes can autonomously discover and retrieve the given NF/SF in a *distributed* manner and execute it *locally* on the specific traffic flow. By not sending a request to the SDN Controller, lower latency can be ensured to flows that require timely processing (eg, interactive games, IoT data collection),[8] and network signaling can be reduced, with a non-negligible benefit to the huge amount of traffic that 5G will handle. Decisions can be taken by ICN nodes according to some local measurements that may also feed the SDN Controller for a global monitoring. As a result, large traffic volumes can be served in a scalable and reliable manner.

3.2 | The ICN-5G node model

Each ICN-5G node implements the model in Figure 1, which is based on the NDN reference implementation[2]. The NDN legacy data structures described in the following are extended to make the node architecture *5G-ready* by enabling it to manage both *named content retrieval* and *named functions retrieval/execution*.

The *Content Store* (CS) is extended with the capability to cache (and manage) *function codes* besides generic contents. A function F, whose code is stored in a node N, can be tagged as active or not in the CS. If F is *active,* then N can act as a provider for that function, meaning that it can run the function and advertise its availability in the neighborhood. If F is *inactive,* then N only answers to Interests that require the function code but cannot run it locally, for example, because of a lack of available resources.

The *Pending Interest Table* (PIT) records all incoming unsatisfied Interests and tracks the related arrival time; it also contains recently satisfied Interests for loop detection and measurement purposes. When a Data packet consumes the relevant Interest, the PIT records the *provisioning time*; otherwise, if the Data packet does not arrive within a predefined timeout (ie, the Interest *lifetime*), the Interest is marked as unsatisfied. We extend the PIT management to explicitly take into account the function execution capability of a node. Namely, depending on the Interest type, the associated lifetime may vary from few milliseconds (eg, for content/code Data packet retrieval) to several seconds or minutes (eg, for a CPU-intensive function execution).

The *Forwarding Information Base* (FIB) is normally used to route Interests toward potential provider(s) through one or more next-hop records. Each entry retains a name prefix and, correspondingly, a collection of outgoing *faces* and related routing costs like the smoothed round trip time (SRTT) on the path toward the provider. Faces are ordered by ascending cost. NDN distinguishes between *network* and *application* faces. The latter can be targeted for a local function execution or for the generation of content not available in the CS.

The *Routing Information Base* (RIB) records: (1) *static* routing information that can be configured manually or registered by applications and (2) *dynamic* routing information updated by the routing protocol. Here, we imagine that the SDN Controller can also change dynamically RIB entries in SDN-enabled NDN nodes. The *RIB Manager* handles the RIB and updates the FIB when needed, that is, it calculates the next hops for FIB entries.

The *Strategy Choice Table* (SCT) maintains the forwarding strategy associated with each namespace; indeed, different services may require different forwarding semantics, for example, low-latency, bandwidth-hungry. The *Strategy Choice (SC) Manager* is the software component in charge of the SCT management. In our vision, this component is the *key* for the integration of ICN in the 5G context; indeed, it may trigger autonomous *local* decisions in the node based on per-name prefix measurements, conveniently stored in a *Measurement Table*, or implement SDN-driven *centralized* decisions. Namely, in SDN-enabled nodes, the envisioned SC Manager interacts with the SDN controller that may configure specific forwarding strategies for given name prefixes, dynamically set and unset some of them, or add new ones at run time. Specifically, accessing information from the FIB and PIT, the SC Manager can trace the *popularity* of both contents and functions (from the request rate), the provisioning time, and the unsatisfied Interests; moreover, it can monitor the CPU/storage load in the node. Based on such measurements, the SC Manager can autonomously modify some configurations set by the SDN Controller. Specifically, it can handle: (1) the content/function code caching and replacement policies and (2) the local function activation/deactivation; for example, it may decide to locally execute those popular functions that would exceed the service latency requirements if executed remotely or it may stop some other functions to avoid the node overload. Basically, the SC Manager is in charge of solving short-term issues without waiting for a configuration update from the SDN Controller. For this reason, it can efficiently manage local communications, for example, between in-network neighboring nodes or between NDN devices (SDN enabled or not) interacting in a device-to-device mode at the access network. The SC Manager in a provider can trigger the advertisement of services deployed locally and also decide to satisfy or not satisfy the service requests received from its neighbors. As mentioned earlier, in the envisioned ICN-5G architecture, the SC Manager and the SDN Controller may interact. Periodically, the SDN Controller requires status information from the SC Manager by sending Interests with a signaling namespace, properly defined at the network bootstrap. The SC Manager replies with Data packets that include the node configuration with statistics about the number of satisfied requests and their provisioning time. In this way, the SDN Controller maintains a global view of the network and sets up new rules or updates the existing ones to further improve the performance.

3.3 | ICN-5G operations

3.3.1 | Naming

Well-defined hierarchical name prefixes can be used to distinguish the name-based request (Interest) type: content retrieval, function code retrieval, or function execution. A function execution over content to be retrieved can also be requested by concatenating the function name after the content name. For example, an Interest with name */campus/buildingA/temp/avg10* indicates that an average operation is required over 10 temperature values collected from building A of the campus.

3.3.2 | Interest and data processing

At the Interest reception, each request type triggers a different kind of processing. The legacy NDN forwarding fabric can be applied for content or a function code retrieval. The function code, like any content, can be segmented in a sequence of Data packets, whose names are defined in a catalogue file (ie, a manifest). Vice versa, in case of a function execution request, the SC Manager will first check in the CS if the function code is available and if it is active locally. If so (ie, there is an application face for that function name in the FIB), the SC Manager controls the current node load stored in the Measurement Table and calculates the estimated provisioning time. If the service requirements are met, then it accepts the request and triggers the local function execution; otherwise, it checks for an outgoing network face in the FIB. If a matching is found, the Interest is forwarded, and a PIT entry is created. Additionally, the traversed node retains statistics about the function popularity (ie, how many requests have been received for it) that are stored in the Measurement Table. If no matching is found in the CS or in the FIB, a negative response in the form of a NACK packet will be sent back. When the Interest is forwarded and the result arrives back, the receiving SC Manager calculates the provisioning time and assesses if the time execution has met the latency requirement of the requesting application. This information is included in the Measurement Table.

3.3.3 | Function migration

If a function F is tracked as popular, the remote service provisioning is expected to be slow due to the high number of requests; so, if the node has the necessary resources, then the SC Manager may decide to retrieve the F code (as specified before) and execute it locally. On the contrary, if the function is no largely requested and/or the node becomes overloaded, or simply unavailable, F can be locally disabled. Not any function can be executed in any node; during the bootstrap, the SDN Controller sends a catalogue of *permitted* functions to each node, which can be also modified at run time.

4 | EXEMPLARY USE CASE

The following use case shows how the ICN-5G framework works in practice. To entertain his child in the backseat with a cartoon, while traveling, Bob starts a video smartphone app that requires a Disney movie in high definition. Similar to YouTube, which uses progressive video streaming, we assume that the client application downloads the content into a buffer in the background. If the buffer becomes empty, the video playback is stalled, thus deeply affecting the Quality of Experience (QoE). Hence, the network is in charge of: (1) locating the video with the requested definition and (2) guaranteeing the QoE, despite the high user speed.

In a traditional IP-based approach, the request addressed to the server is received by an edge-router, which asks the SDN Controller to select the path the flow has to go through and sets up the states on the intermediate switches. To ensure the best QoE, 2 additional functions are needed: (1) *a DPI-based controller*, which checks for video content and lets the network prioritize it with respect to delay-tolerant traffic, and (2) *an optimizer,* which transcodes the video to the requested format on the fly. If the video server does not own the optimizer function, the content needs to reach a middlebox that executes the service on its behalf, while the content goes back to the requesting user along the UP processing. The path toward the middlebox needs to be set up by the SDN Controller as well. Things get worse due to the high mobility of the consumer, which can change the point of attachment, causing service disruption. As a result, the dynamicity and flexibility of the network are compromised, and the latency requirement could be not satisfied.

In the ICN-5G network, the request is carried out in an Interest, with a composed hierarchical name that includes the name of the movie and its format, for example, */video/scroogeMovie/mp4/720p*. The packet is forwarded in the backhaul network toward the content source; there is no need for a DPI service function as each ICN node may identify the packet priority from the first name component, "video", and apply a customized forwarding strategy. If an intermediate router *R* (even the BS) realizes it has a full-name matching in its CS, it can immediately answer the request. Instead, a partial name prefix in the CS, for example, */video/scroogeMovie/mp4/*, means that *R* has the content but not the right format. In this case, *R* has 2 choices: it can simply forward the Interest toward the content source, if there is an available route (as set by the SDN Controller), or it can download the conversion function and execute it locally. By analyzing the node status and the network conditions, the SC Manager makes the best decision. For instance, from the Measurement Table, the SC Manager realizes that the 720p conversion function has been frequently requested in the last period, and it has the proper resources to execute it. By analyzing the FIB entry toward the content source, it realizes that the route is congested due to the long SRTT, while the route toward the function code has a very low cost. As a result, the SC Manager decides to download the function and execute it locally.

5 | CONCLUSIONS

This paper discusses how ICN features could natively fulfill 5G requirements. A high-level architecture has been proposed that candidates ICN as a 5G networking solution for managing content retrieval and virtualized functions execution.

NOTES

1. Hereinafter, we will refer to ICN and NDN interchangeably.
2. https://named-data.net/wp-content/uploads/2016/10/ndn-0021-7-nfd-developer-guide.pdf

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