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Information-Centric Networking: Research and Standardization Status

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ABSTRACT Information-centric networking (ICN) is a new approach to networking contents rather than devices that hold the contents. It has recently attracted much attention of network research and standardization communities. National and multi-national funded research projects have progressed worldwide. International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) started ICN standardization activities in 2012. In parallel, the standards-oriented research cooperation is progressing in the Information-Centric Networking Research Group (ICNRG) of the Internet Research Task Force (IRTF). All these global efforts have been collectively advancing the novel network architecture of ICN. However, there are very few surveys and discussions on the detailed ICN standardization status. To update the reader with information about the ICN research and standardization related activities, this paper starts with the history of global activities on ICN from 2010, giving references to various projects. It then describes the recent progress in the standardization of ICN component technologies in ITU-T and various documents produced by ICNRG. Lastly, it discusses the future directions for progressing ICN.

INDEX TERMS Information-centric networking, data aware networking, standardization, ICNRG, ITU-T.

I. INTRODUCTION

These days we use networks more for content retrieval than for direct communication between people or with a device or server [1]. This trend has demanded a new network architecture optimized for content retrieval, which resulted in the emergence of a new network architecture named Information-Centric Networking [2], [3].

The ICN concept has born in the era that more and more users are shifting their interests to the content itself rather than the location or server where contents are stored. This content-centric behavior of user applications has rendered the point-to-point communication paradigm of IP networks inefficient. By naming contents [4] in the network layer, ICN natively supports in-network caching mechanisms [5], [6] to facilitate efficient usage of network resources and timely delivery of contents to end users. In other words, users send their requests containing the content names and obtain the content from the nearest ICN router that has stored a cached copy of the content, instead of from the content owner's servers. Unlike the IP addresses, the content names are not associated with a particular location in the network and the content names are decoupled from communication session, ICN simplifies the process of supporting end-user mobility [7] without requiring to re-establishing communication sessions. In addition, ICN secures each data object by the publisher's signature [8]–[10], rather than securing the communication channel between two endpoints [11]–[13]. ICN, relying on name-based routing, in-network caching and data-self security, possesses

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great potential to address some of the problems encountered with IP-based protocols, and is regarded as a promising architecture of future Internet [14], [15]. Its merits include: 1) providing better performance in network traffic control, 2) supporting content-oriented access methods and intermittent connections, and 3) simplifying security procedures by self-contained data security. Although ICN activities started about a decade ago [16], it is still in its early stage, and many challenges are yet to be addressed. For example, although in-networking caching greatly improves the performance of ICN, effective cache management methods are still an open issue. Similarly, in ICN content will be pervasively cached in the network to get efficient and timely delivery to end users. However, how to guarantee the users' privacy in the cached network is a challenging issue to be addressed. In recent past years, many ICN-related projects have investigated several issues and proposed some solutions to deploy ICN in network infrastructure [17], [18].

Many national and multi-national funded research projects worldwide have worked together to boost the research activities on ICN. For instance, early ICN projects in the European Union (EU), which were supported by the Seventh Framework Programme (FP7) funding, followed an evolutionary approach to realizing ICN while cooperating with the current IP networks [19]. On the other hand, the National Science Foundation (NSF) in the USA funded ICN projects followed a revolutionary approach with a slogan of "clean slate design" [20]. Similarly, Defense Advanced Research Projects Agency (DARPA) in the USA also funded the project named Content-Based Mobile Edge Networking to develop the network services and transport architecture to enable efficient and transparent distribution of contents in mobile ad hoc network environments [21].

In parallel with the efforts of national research projects, International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) initiated activities for the standardization of the novel network architecture under the name of Data Aware Networking (DAN) [22] in early 2012. DAN has attempted to present a new network architecture that would satisfy "data awareness", which is one of the four design objectives of future networks specified in Y.3001 [23]. In the research community too, the concept of ICN has been investigated under various names, such as Network of Information (NetInf) [24], Named Data Networking (NDN) [16] and Content Centric Networking (CCN).

Around the same time of the beginning of standardization activities in ITU-T, the Information-Centric Networking Research Group (ICNRG) [25] was formed in Internet Research Task Force (IRTF) in August 2012 to promote the global research and standardization activities on ICN. IRTF is not a standardization organization but an international standards-oriented research community, which is composed of various research groups. The advent of ICNRG helped in channelizing the global common interests on ICN to unify different types of network architectures for content dissemination being studied under the name of ICN by the global

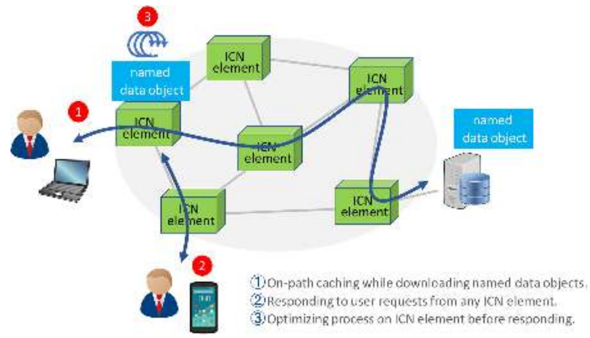

FIGURE 1. ICN basic operation presented in Y.3033.

research community. Similarly, the European Telecommunications Standards Institute (ETSI) [26] investigated ICN issues in two groups: Next Generation Protocols (NGP) and the Internet of Things/Machine-to-Machine communications (IoT/M2M).

These global research activities, which are still ongoing, could be instrumental in forming the foundation of subsequent global standardizations. This article aims to provide appropriate guidance to future ICN realizations and developments by describing the early global activities of ICN from three different perspectives: international research activities in EU and USA, international standardization activities in ITU-T, and international research cooperation in IRTF.

This article is organized as follows. The ICN concept will be briefly introduced in Section II. Section III describes international ICN research projects that have spread awareness about ICN worldwide. Section IV introduces standardization activities in ITU-T for ICN under the name of DAN. The history and activities of ICN research in ICNRG are elaborated in Section V. Section VI discusses the future directions for progressing ICN, and finally Section VII concludes this paper.

II. BASIC CONCEPTS OF ICN

ICN was initially proposed to revolutionize the Internet architecture with a new network model for the native support of accessing named data objects. Due to direct access to data objects, inexpensive and ubiquitous in-network caching and replication are enabled, which result in improved efficiency and better scalability in terms of data distribution and network bandwidth utilization. To achieve the benefits, the following technical research challenges of ICN have been identified: how to name data objects to uniquely identify them (known as naming), how to locate named data objects and deliver them to the clients (routing), how to secure named data objects that are widely distributed in the network (security), how to support mobility in an information-centric and location-independent manner (mobility). We briefly introduce the architectural components of ICN below by using Figure 1.

A. NAMING

Naming data objects is a key concept for ICN, which enables to identify data objects independently of their location.

To uniquely name a data object in ICN, there are two major approaches: hierarchical naming scheme, and flat naming scheme. The former is rooted in the prefix of a publisher, which enables aggregation of routing information and enhances the scalability of a routing scheme. The latter uses a hashing value of a data object, e.g., its content or name. Due to the use of a hashing value, the flat naming scheme produces a fixed length name for each data object, which enhances the speed of name lookup time.

B. ROUTING

ICN routing consists of three steps: (1) name resolution, (2) discovery, and (3) delivery. In the first step, the name of a data object is translated into its locator. Then, the discovery step routes a user request to the data object. In the final step, the requested data object is routed to the client. Depending on the combination of these steps, ICN routing is categorized mainly into two; namely, route by name routing (RBNR) and lookup by name routing (LBNR).

C. MOBILITY

ICN mobility aims to enable clients to continuously receive content without any perceptible disturbance in ICN applications. Due to a receiver driven content retrieval in ICN, a change in the physical location of a client does not interrupt continuous content reception. On the other hand, server-side mobility is challenging to support. In particular, ICN mobility needs to closely work with ICN routing to discover an identical data object, which is identical to the one being transmitted.

D. SECURITY

Data objects can be retrieved from anywhere in ICN due to in-network cache and so their origins cannot always be a trusted entity. For this reason, a security mechanism should be provided to make sure that the retrieved data object has not been maliciously modified since its publication from the authentic publisher. In addition, data origin authentication, i.e., verifying the integrity between a data object and its publisher, is another axis of ICN security. Failure of these security mechanisms opens several attacks, e.g., DoS attacks, by injecting contaminated content into the network.

III. ICN RESEARCH PROJECTS

The national and regional funding organizations have supported various ICN research projects. In EU, ICN projects had been carried out under the names of COMET [27], ALICANT [28], COAST [29], CONVERGENCE [30], SAIL [31] and PURSUIT [32] supported by FP7. In the USA and Japan, they were known as NDN/CCNx [33] and GreenICN [34], respectively. These projects completed around the end of 2013 after 2-3 years of the project periods. We call this period as the first phase of ICN research activities.

The ICN projects in the first phase produced research outcomes regarding the architectural components of several ICN realizations such as NDN, CCNx, NetInf, and PSIRP [35]. Moreover, the operation of the ICN realizations has been demonstrated within a small network composed of five to ten nodes. The projects during this phase aimed to verify the feasibility of newly proposed architectures. The overview of these ICN projects is shown in Table 1.

TABLE 1. ICN research projects in the first phase in EU & US.

	Project Name	Project Start	Project Duration
EU	COMET	Jan 2010	3.0 years
	COAST	Feb 2010	2.5 years
	ALICANTE	Jan 2010	3.0 years
	SAIL	Aug 2010	2.5 years
	PURSUIT	Sep 2010	2.5 years
	CONVERGENCE	Jun 2010	2.75 years
US	NDN	Sep 2010	3.0 years
EU-JAPAN	Green ICN	Apr 2013	3.0 years

The second phase of ICN projects began from 2014 and early 2015 with next-phase of ICN projects such as NDN-NP [36], RIFE [37], POINT [38] and ICN 2020 [39]. The main aim of these projects was to provide proof of ICN operational concept at a reasonable scale with realistic service scenarios. Thus, various ICN use-case scenarios have been proposed [40], [41] and their prototypes have simultaneously been verified on large scale test-beds such as NDN Testbed [42]. The overview of the second ICN projects is shown in Table 2.

TABLE 2. ICN research projects in the second phase in EU & US.

	Project Name	Project Start	Project Duration
EU	RIFE	Feb 2015	3.0 years
	POINT	Jan 2015	3.0 years
US	NDN-NP	May 2014	3.0 years
EU-JAPAN	ICN 2020	Jul 2016	3.0 years

Next we elaborate two latest ICN related EU-Japan projects: GreenICN and ICN2020.

The GreenICN project [34] was one of the first set of EU FP7 - Japan collaborative research projects, which started in April 2013 and completed in May 2016. This project was dedicated to working on highly scalable and energy-efficient methods for ICN networks and devices. It leverages the designed infrastructure to support two exemplary application scenarios (also illustrated in Figure 2): 1) After disasters (such as hurricanes or tsunamis), it is important to effectively distribute disaster notifications and critical rescue information under stringent conditions of limited availability of energy and communication resources. The challenge in this scenario is how to improve the ability to exploit fragmented networks under intermittent connectivity. 2) Scalable and

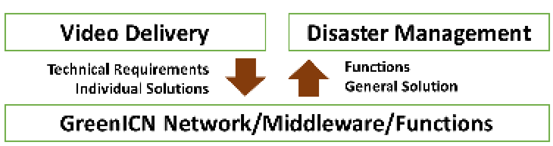

FIGURE 2. Green ICN concept presented in [43].

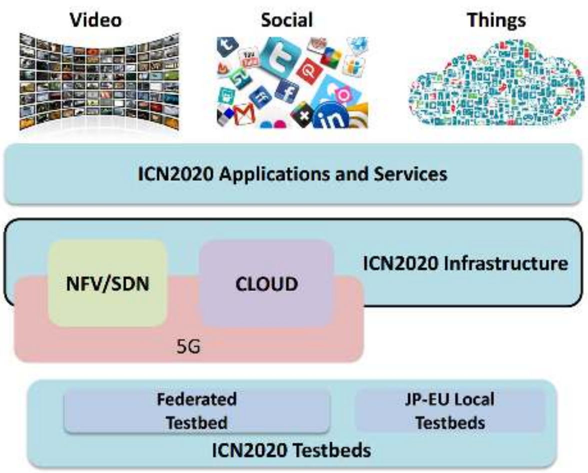

FIGURE 3. ICN2020 concept presented in [39].

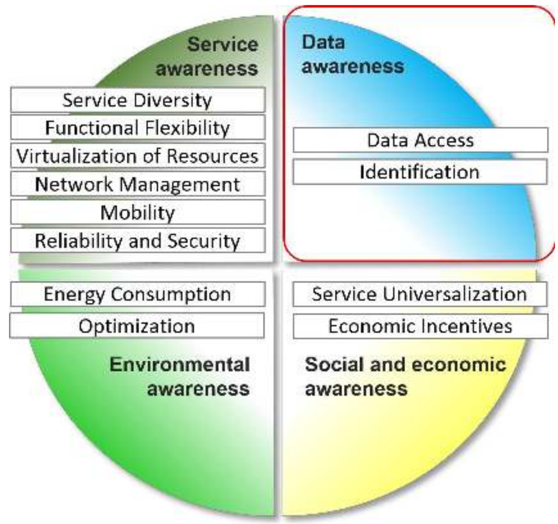

FIGURE 4. Four objectives and 12 design goals of future networks presented in Y.3001.

efficient publish/subscribe video delivery scenario. The challenge in this scenario is to achieve both scalability and energy efficiency in both normal and disaster situations. In addition, the GreenICN project released a functionality-rich API to drive the creation of new applications and services to promote adoption of ICN by industry and consumers in the EU and Japan.

The ICN2020 project [39] started from July 2016 was a 3-year collaborative research project supported by EU FP7-Japan joint funding. Figure 3 shows the ICN2020 concept. This project is based on a large number of ICN studies to achieve the following six main goals [43]: 1) Design and develop a set of exemplary main applications with a special focus on video delivery and social networks; 2) Design and develop key features of IoT applications and ICN services; 3) Adapt ICN to complement 5G; 4) Improve/resolve solutions to vital functions of ICN based Infrastructure; 5) Realistic experiments on large scale local and global federated testbeds; 6) Stimulate general deployment of ICN in the real world, e.g., by integrating specific ICN concepts and solutions in POCs by industrial partners during the project lifetime.

IV. ICN STANDARDIZATION ACTIVITIES IN ITU-T SG13

ITU-T Study Group 13 (SG13), which is leading the future network standardization activities in ITU-T, started the activities on data aware networking with the establishment of the Focus Group on Future Networks (FG-FN) in 2009. The FG-FN's output document was later published as Recommendation ITU-T Y.3001 "Future Networks: Objectives and design goals" [23], which is considered as the vision document of future networks. Y.3001 describes four objectives and twelve design goals for future networks as shown in Figure 4. One of the objectives is data awareness, which aims at optimizing the handling of enormous amounts of data in a distributed networking environment and enabling users to access desired data quickly, efficiently, reliably, and accurately, regardless of their location.

In February 2012, ITU-T SG13 initiated a new draft to specify data aware networking framework for the realization of the data awareness objective of future networks. Data aware networking (DAN) is formally defined as a new network architecture whose essence lies in the name based communication that routes a data object in the network by its name or identifier (ID). The name-based routing enables not only end hosts but also intermediate network nodes to be aware of user requests, and so individual DAN network elements are able to cache or store data objects. Thus, users can retrieve them in the most efficient manner considering various performance metrics, e.g. hop counts or delay. In November 2013, the draft was approved and became Recommendation ITU-T Y.3033 "Framework of data aware networking for future networks" [44].

In February 2014, a new draft Supplement to ITU-T Y.3033 was initiated to list prominent use case scenarios, their benefits, and migration paths from the current networks to DAN. It was approved in 2016 as Supplement 35 to ITU-T Y-series Recommendations [40]. To specify the requirements and capabilities to support the use case scenarios described in this Supplement, another new Recommendation Y.3071 was initiated in April 2015.

ITU-T SG13 then started a new Study Period (2017-2020). In this Study Period, it has set up Question 22 (Q22/13) with the responsibilities of standardizing ICN technologies. In February 2017, ITU-T SG13 approved Recommendation ITU-T Y.3071 "Data aware networking (Information centric networking) - Requirements and capabilities" [45], which has been considered as the first Recommendation specifying the technology for International Mobile Telecommunication (IMT)-2020 or 5G networks. In addition, Q22/13 is expected to progress the standardization of ICN related issues partially derived from the deliverables of Focus Group on IMT-2020. Below we describe four Recommendations relevant with ICN, which are also illustrated in Figure 5.

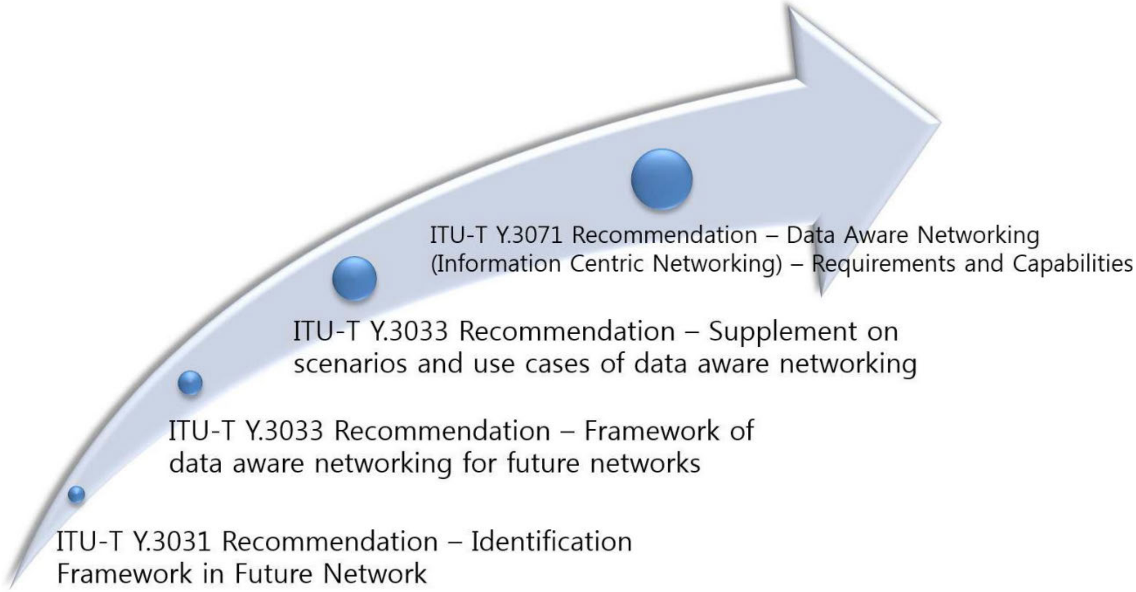

FIGURE 5. ITU-T SG13 activities regarding data aware networking.

A. Y.3031: IDENTIFICATION FRAMEWORK IN FUTURE NETWORK

Recommendation ITU-T Y.3031 ''Identification framework in future network'' [46], approved by ITU-T in February 2012, was developed based on the deliverable of FG-FN. It specifies the identification framework and general requirements for the future networks envisioned in Recommendation ITU-T Y.3001. It also provides descriptions of the user, data, service, node, and location identifiers being used in the current networks and FN-related projects.

All these identifiers (ID) are well accommodated in the ID spaces of the identification framework as shown in Figure 6. The framework also includes IDs mapping registries, IDs discovery service, and ID mapping service. The IDs mapping registries store various types of IDs belonging to a communication object. The ID discovery service helps the communication objects to discover IDs related to their own or peer communication objects. The ID mapping service performs the mapping of IDs of one category with the IDs of other categories. As shown in the figure, the identification framework enables various communication objects to be connected through heterogeneous types of physical networks.

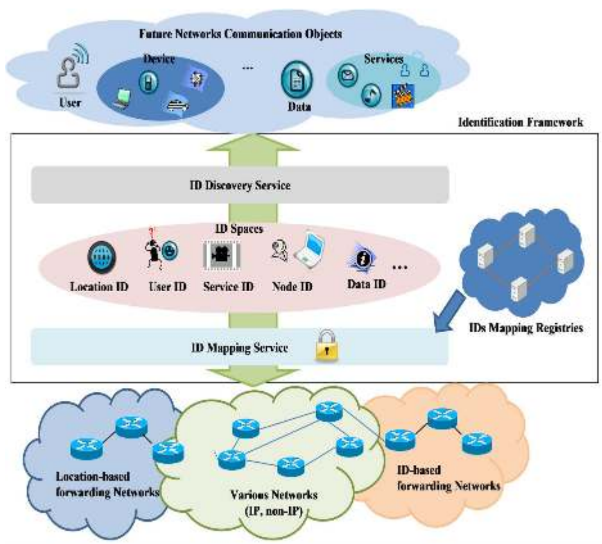

FIGURE 6. Illustration of identification framework in future network presented in Y.3031.

B. Y.3033: FRAMEWORK OF DATA AWARE NETWORKING

Recommendation ITU-T Y.3033 ''Framework of data aware networking'' [44] describes data aware networking pertinent to the data awareness aspect of future networks envisioned in Recommendation ITU-T Y.3001. It gives an overview of DAN, which includes general properties and high-level requirements of DAN such as naming, routing, caching, security, mobility, application programming interface, and transport.

It clarifies that the essence of DAN lies in the name based routing that routes a data object in the network by its name or ID, which enables not only end hosts but also intermediate nodes between them to be capable of responding to user requests. Thus, ''data-aware'' in the name of DAN means that the intermediate network elements possess the capability of recognizing the data name or ID as well as its attributes (e.g., file extension) and make a decision based on them. The decisions include: 1) Routing of user requests and the corresponding responses, 2) Responding to user requests directly if the requested data object is available, and 3) Processing of user requests and the corresponding responses. The term "processing" includes any optimization process requested by user and the corresponding responses prior to transmitting them.

C. SUPPLEMENT 35 TO Y.3033: DATA AWARE NETWORKING - SCENARIOS AND USE CASES

Supplement 35 to Recommendation Y.3033 "Data aware networking: scenarios and use cases" [40] introduces the scenarios and use cases of DAN. It provides a technical context that is expected to be useful to the discussion on architectural requirements of DAN in further documents to be developed. It also clarifies the roles and interactions of DAN entities for services delivered on DAN.

It contains the following seven use-case scenarios: 1) content dissemination, 2) sensor networking, 3) vehicular networking, 4) networking in a disaster area, 5) advanced metering infrastructure in smart grid [47]–[49], 6) proactive video caching, and 7) in-network data processing. The list of the use-case scenarios is not intended to be exhaustive but sufficient enough to provide the understanding of DAN operation.

D. Y.3071: DATA AWARE NETWORKING (INFORMATION CENTRIC NETWORKING)-REQUIREMENTS AND CAPABILITIES

Recommendation ITU-T Y.3071 [45] "Data aware networking (Information centric networking): Requirements and capabilities" is the first Recommendation in ICN series in ITU-T where the term "Information centric networking" is explicitly mentioned in the title.

ITU-T Y.3071 aims at identifying the capability components of DAN to realize the use case scenarios introduced in the Supplement 35 to Y.3033 [40], and also to understand the requirements of individual capabilities components for their realization.

For this reason, ITU-T Y.3071 specifies the requirements and capabilities of data aware networking, which contains the following seven categories of requirements: 1) forwarding, 2) routing, 3) mobility, 4) security, 5) management, 6) miscellaneous, and 7) user case specific. It also defines the following five major capabilities: 1) data capability, 2) control capability, 3) security capability, 4) management capabilities, and 5) application capability. Figure 7 shows the functional view of DAN capabilities in specified in ITU-T Y.3071.

E. ITU-T FG IMT-2020: 5G WITH ICN

ITU-T Focus Group on IMT-2020 (FG IMT-2020), a temporary group open for the participation of all experts both from inside and outside of ITU-T membership, was established in May 2015. In its one and half year lifetime consisting of two phases, FG IMT-2020 studied network aspects of emerging IMT-2020/5G technologies as pre-standardization activities.

FG IMT-2020 was composed of three working groups (WGs) and one of them studied ICN as one of "emerging networking technologies" and its application to IMT-2020/5G networks. This WG explored the various features of

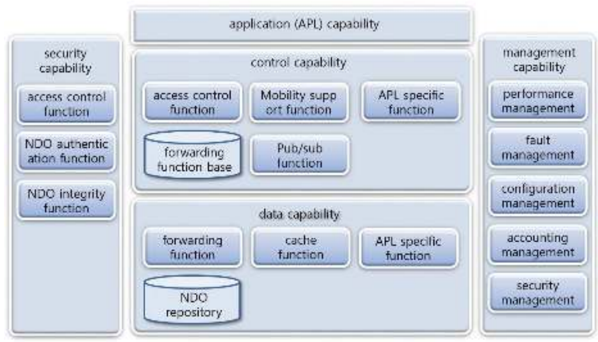

FIGURE 7. Functional view of DAN capabilities in Y.3071.

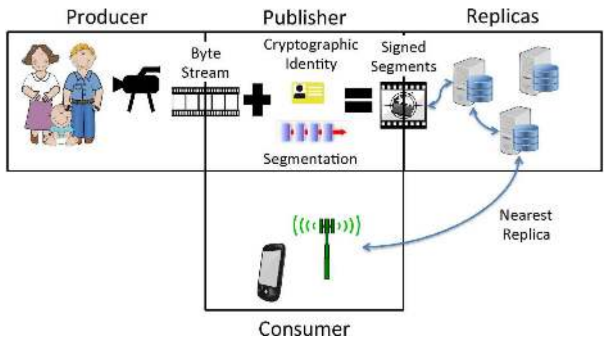

FIGURE 8. Typical ICN architecture illustrated by ICN working group in the Focus Group on IMT-2020 [50].

ICN technology in the context of meeting the visionary goals of IMT-2020 network. ICN was considered useful to satisfy the network requirements of IMT-2020 to support three service scenarios of enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC). FG IMT-2020 identified ICN as a promising technology with the capability to enable IMT-2020 networks supporting very large-scale heterogeneous devices, Internet of things (IoT), new mobility models, edge computing and end device self-configuration.

FG IMT-2020 considered the architectural components of ICN as shown in Figure 8. These components are content producers, content publishers, content replicas, and content consumers. Their interaction for a typical service scenario of video transmission is illustrated in the figure.

FG IMT-2020 produced the following two deliverables in its two phases of activities: (1) standardization gap analysis, and (2) a list of ICN proof-of-concept (PoC). ITU-T Study Group 13 compiled these two deliverables into a single document and published it as Supplement 47 to Y-series Recommendations [51]. The fifteen standardization gaps identified by FG IMT-2020 are as follows (also shown in Table 3): 1) Considering ICN as a protocol for IMT-2020 networks, 2) Robust header compression for air interface, 3) ICN-aware Serving Gateway (S-GW), 4) ICN-aware Mobility Management Entity (MME), 5) ICN-aware Packet Data Gateway (P-GW) operation, 6) ICN protocol execution in slice, 7) ICN lawful interception, 8) ICN mobility and routing,

TABLE 3. Standardization gaps identified by focus group on IMT-2020.

Gap 1	Considering ICN as a protocol for IMT-2020 network
Gap 2	ICN – Robust header compression for air interface (PDCP)
Gap 3	ICN – Mobility anchoring (ICN aware S-GW)
Gap 4	ICN – Mobility (ICN-aware MME)
Gap 5	ICN – Protocol (ICN-aware P-GW operation)
Gap 6	ICN – Protocol execution (slice)
Gap 7	ICN – Lawful intercept (specify what to capture)
Gap 8	ICN – Mobility and routing
Gap 9	ICN – UE provisioning
Gap 10	ICN – Managing IMT-2020 Self Organizing Network (SON)
Gap 11	ICN – Operations and management (common interfaces)
Gap 12	ICN – Operations and management (SDN/OpenFlow)
Gap 13	ICN – Security (authentication and encryption)
Gap 14	ICN – Security (encryption)
Gap 15	ICN – QoS (demand based)

TABLE 4. Proof-of-concepts investigated by Focus Group on IMT-2020.

PoC A	ICN enhanced mobile video at the network edge
PoC B	Function chaining system in ICN
PoC C	End-to-end ICN service orchestration with mobility for IMT 2020
PoC D	IP services over ICN
PoC E	ICN transport on millimeter wave networks
PoC F	Data service using ICN in IMT-2020

9) ICN users equipment (UE) provisioning, 10) ICN managing IMT-2020 self-organizing network (SON), 11) ICN operation and management of common interfaces, 12) ICN operation and management of SDN/OpenFlow, 13) ICN security – authentication, 14) ICN security – encryption, 15) ICN quality of service. Similarly, Supplement 47 listed the following five proofs-of-concept (PoCs) (also shown in Table 4): A) ICN enhanced mobile video at the network edge, B) Function chaining system in ICN, C) End-to-end ICN service orchestration with mobility for IMT 2020, D) IP services over ICN, and E) ICN transport on millimeter wave networks. Additionally, Supplement 48 [52], which was produced by ITU-T Study Group 13 later on the basis of a new input contribution from China, describes another PoC of named data (e.g., IoT service data) service delivery by ICN in IMT-2020. It has been added to Table 4 as PoC F.

PoC A specifies DASH video delivery as a use case of ICN and demonstrates the benefits of ICN mobility management, in-network control (rate/loss) and network-assisted bitrate adaptation for a multi-homed UE. It leverages ICN features to effectively reduce transport cost through the exploitation of native edge caching and multi-point/multi-source communications over the backhaul. Similarly, PoC B leverages ICN features and capabilities to dynamically construct functional chains to effectively deliver video service. PoC C demonstrates ICN's inherent feature of seamless mobility as part of the network architecture, avoiding the necessity of a specific gateway function or tunneling. Name-based routing enables the UE to flexibility move across administrative domains. PoC D enables the multicast delivery of HTTP responses for personalized viewing of video content, enabling the reduction of user experienced latency through the flexible placement as well as quick activation of surrogate HTTP servers within the network and closer to UEs. PoC E demonstrates ICN-based high-throughput communication services of IMT-2020 over millimeter wave (mmWave)-based wireless systems. Similarly, for enabling ICN-based efficient delivery of named data service, PoC F specifies an implementation of the enhanced name resolution system on distance-constrained containers for resolving the data names into addresses more efficiently.

These six PoCs address six of the fifteen standardization gaps from different approaches. Table 5 shows the mapping of PoCs with the standardization gaps. As shown in the table, two standardization gaps of using ICN in IMT-2020 to deliver communication services, and mobility and routing are relevant with all the PoCs. These standardization gaps are the common issues, where ICN can bring about significant improvements compared to the anchor-based mobility of the current 4G networks. Similarly, ICN slice and UE provision gaps are relevant with PoC A, while ICN OAM for SDN and OpenFlow and authentication are relevant with PoC D. PoCs B and C address ICN authentication and OAM SDN and OpenFlow, respectively, besides the two common standardization gaps mentioned earlier. As ICN technology starts getting deployed new approaches to addressing many of these standardization gaps would be gradually standardized in SDOs.

F. RECENT ICN ACTIVITIES IN ITU-T STUDY GROUP 13

ICN related activities are progressing in the ITU-T Study Group 13 Question 22. It has recently produced Recommendation ITU-T Y.3072 [53] "Requirements and capabilities of name mapping and resolution for information-centric networking in IMT-2020". It specifies the requirements and capabilities of name mapping and resolution to achieve high performance of low latency and scalability for managing a large number of named objects. Similarly, there are five new Recommendations currently in progress. They are specifying the frameworks of service function chaining in ICN and directory service for object name management, and requirements and capabilities of ICN-based routing and forwarding, ICN-enabled transport layer, and edge networks. The ICN functional architecture and detail specifications are yet to be developed in ITU-T.

V. ICN STANDARDS-ORIENTED RESEARCH COOPERATIONS IN ICNRG OF IRTF

In August 2012, the first ICNRG meeting was held under the umbrella of IRTF, which aimed to provide a forum for the exchange and analysis of ICN research ideas and proposals. Although ICNRG is not a standardization group, the advent of

TABLE 5. Mapping standardization gaps with proof-of-concept.

	Standardization gaps	Proof-of-concept					
		PoC A	PoC B	PoC C	PoC D	PoC E	PoC F
1	ICN in IMT2020	✓	✓	✓	✓	✓	✓
2	ROHC						
3	ICN S-GW						
4	ICN MME						
5	ICN P-GW						
6	ICN slice	✓					
7	ICN lawful intercept						
8	ICN mobility and routing	✓	✓	✓	✓	✓	✓
9	ICN UE provision	✓					✓
10	ICN management SON						
11	ICN OAM common interfaces						
12	ICN OAM SDN and OpenFlow			✓	✓		
13	ICN authentication		✓		✓		✓
14	ICN encryption						
15	ICN QoS						

ICNRG unified all research activities regarding such network architectures under the name of ICN.

Soon after the establishment of ICNRG, three major drafts were initiated by individual chairs in ICNRG: 1) ICN Survey document, 2) ICN Research Challenges document, and 3) ICN Baseline Scenarios and Evaluation Methodology document. Figure 9 describes ICNRG initial documents and final status.

The aim of the ICN Survey document is to provide a survey of different approaches and techniques of ICN. It has relatively less completeness compared to the other two documents although several ICN survey literature is available. The ICN Research Challenges document describes the ICN problem statement, the main concepts, and research challenges in depth, especially to expose requirements that should be addressed by future ICN research works. Lastly, the ICN Baseline Scenarios and Evaluation Methodology document was initially intended to define reference baseline scenarios to enable performance comparisons among different approaches. However, the document was dividedinto two in July 2013: 1) ICN Baseline Scenarios document that

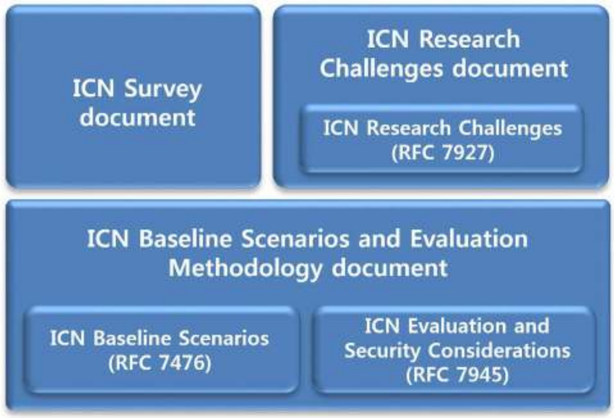

FIGURE 9. ICNRG initial documents and final status.

describes ICN application scenarios, and 2) ICN Evaluation Methodology document that deals with evaluation methodology. The former and the latter became an Information RFC 7476 [41] and Information RFC 7945 [54].

A. RFC 7476: INFORMATION CENTRIC NETWORKING BASELINE SCENARIOS

This document [41] is intended to establish a common understanding of a set of scenarios that can be used as a basis for assessing different ICN methods so that they can be tested and compared with each other while demonstrating their strengths. To this end, many previous performance evaluation studies from ICN literature and documents have been reviewed. Moreover, a variety of aspects are discussed to address the potential of ICN solutions. It includes general aspects such as network efficiency, reduced complexity, increased scalability and reliability, mobility support, multicast and cache performance, real-time communication efficiency, energy consumption savings, and interrupt and latency tolerance. ICN specific aspects are detailed as well, such as information security and trust, persistence, availability, source and location independence.

This document has two main objectives: first, to provide a set of use cases and applications for highlighting opportunities when testing different ICN proposals; and second, to identify key attributes that can be used to evaluate a set of commonly used technologies for ICN. For this reason, this document presents nine scenario categories based on the use cases and assessments that appeared in the peer-reviewed literature. They are: 1) social networking, 2) real-time communication, 3) mobile networking, 4) infrastructure sharing, 5) content dissemination, 6) vehicular networking, 7) delay- and disruption- tolerant networking, 8) internet of things, and 9) smart city.

This document incorporates the views of ICNRG participants and their corresponding texts which have been reviewed by several ICNRG participants, and represents the consensus of the study group. However, this document does not constitute the IETF standard. It is an information document rather than an official document conveying IETF ideas.

As mentioned previously, these scenarios are intended to provide a framework for assessing different ICN approaches. Moreover, three cross-scenarios have been discussed in ICN evaluation studies, which include 1) multiple connected nodes and economics, 2) energy efficiency, and 3) operation across multiple network paradigms.

B. RFC 7927: INFORMATION CENTRIC NETWORKING RESEARCH CHALLENGES

This document [55] describes the ICN research challenges which need to be addressed from a technical perspective including current approaches and their limitations. The document begins with a discussion of problems with host-centric communications, which restricts native support of multi-party communication, e.g. multi-source/multi- destination communication. The concept of ICN, naming data directly, can deal with the issues raised in the host-centric communications.

Nine major research challenges on ICN are discussed: 1) Naming, 2) Security, 3) Routing and resolution system scalability, 4) Mobility management, 5) Wireless networking, 6) Rate and congestion control, 7) In-network caching, 8) Network management, 9) ICN applications. In each challenge, the research problem is initially elaborated in detail to provide insight into the challenge compared to conventional approaches in IP networks. At the end of each challenge, concrete research problems are summarized, which can be potential ICN research topics. In particular, the last challenge, ICN applications, is somewhat interesting. The part introduces three potential ICN application scenarios: web application, video streaming and downloading, and Internet of Things. It discusses which research challenges should be addressed to accommodate the applications in ICN domain. The set of the ICN research challenges remains to be addressed and tackled so that ICN can be successfully deployed step by step in the future.

C. RFC 7945: INFORMATION CENTRIC NETWORKING: EVALUATION AND SECURITY CONSIDERATIONS

This document [54] derived from one of three major documents in ICNRG: ICN Baseline Scenarios and Evaluation Methodology. The document aims to provide an equal footing ground for the evaluation of different ICN approaches, and so it helps researchers in ICN community alike to compare and contrast various ICN designs.

The document is mainly divided into three parts: 1) evaluation considerations, 2) ICN security aspects, 3) evaluation tools. The first part elaborates the problems with the use of conventional approaches for the evaluation of ICN designs. Since ICN has not been deployed commercially yet, various necessary information for ICN research such as topology, traffic patterns, and performance metrics are not available. Thus, it provides choices for the evaluation of ICN designs. The second part describes the ICN security aspects. Since ICN introduces a new paradigm of networking architecture, it results in changes to many aspects of network security.

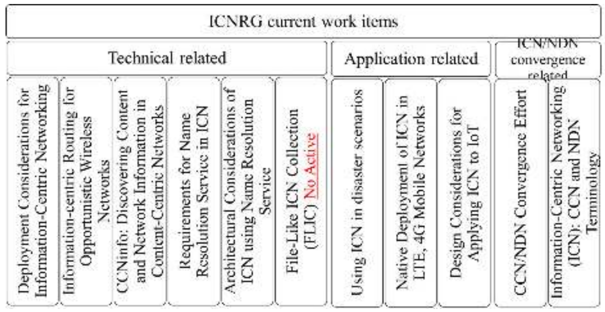

FIGURE 10. ICNRG current work items.

Thus, various ICN research attempts to address the ICN security challenges. The last part introduces various ICN simulation tools and real test beds, which have been widely used in ICN research community.

D. ICNRG CURRENT WORK ITEMS

ICNRG's current main work is to combine ongoing ICN research and solutions that are relevant to the development of the Internet. It will generate a document that guides the experimental activities in the ICN field and begins discussions on ICN applications and network management. This group holds regular physical meetings in conjunction with IETF meetings and related academic conference to deal with currently prioritized work items as below. [25] lists 12 ICNRG current work items and we divided them into 3 groups, technical related work items, application related work items and ICN/NDN convergence related work items, which is also shown in Figure 10.

1) TECHNICAL RELATED WORK ITEMS

For the ICNRG technical related working items, there are a total of 6 work items, one of which has no active and the other 5 work items are mainly dedicated to providing deployment considerations for the next development of ICN, and providing some technical documents on ICN routing protocols, network topologies, in-network caching, and technical requirements and architectural considerations for name resolution services. Details are shown below.

- *"Deployment Considerations for Information-Centric Networking"* provides many deployment considerations in helping the ICN community move into the next step of live deployment.
- *"Information-centric Routing for Opportunistic Wireless Networks"* focuses on the Data reAchaBility BasEd Routing (DABBER) protocol, which has been developed to NDN based routing approaches for opportunistic wireless networks.
- *"CCNinfo: Discovering Content and Network Information in Content-Centric Networks"* discover information about the network topology and in-network cache in CCN.
- *"Requirements for Name Resolution Service in ICN"* and *"Architectural Considerations of ICN using Name*

Resolution Service" discusses the requirements and architectural considerations for Name Resolution Service (NRS) in ICN respectively.

2) APPLICATION RELATED WORK ITEMS

For the ICNRG application-related work items, there are 3 work items and mainly dedicated to working on applying ICN to disaster scenarios, 4G mobile networks and IoT system.

- "Using ICN in disaster scenarios" outlines some of the research directions in applying ICN approaches to deal with large-scale natural or human-made disasters.
- "Native Deployment of ICN in LTE, 4G Mobile Networks" enables the deployment of ICNs in cellular mobile networks by using ICNs in the 3GPP protocol stack.
- "Design Considerations for Applying ICN to IoT" summarizes the general requirements of IoT, and ICN features support these requirements, and then discuss the challenges of implementing an ICN-based IoT framework.

3) ICN/NDN CONVERGENCE RELATED WORK ITEMS

Currently, ICNRG has two work items to start CCN/NDN convergence effort for understanding and documenting current differences and trying to resolve these differences. ICNRG is also working to provide a comprehensive collection for terminology as they are used in the CCNx and NDN projects.

- "CCN/NDN Convergence Effort" documents the differences between CCN and NDN protocols in the document design choices and differences for NDN and CCNx 1.0 implementations.
- "Information-Centric Networking (ICN): CCN and NDN Terminology" outlines the terminology and definitions which have been used in describing the concepts in these two projects (CCN / NDN).

VI. FUTURE DIRECTIONS OF ICN

To promote the wider acceptance and large-scale deployment of ICN, the following issues also need to be addressed [56].

A. COMPATIBILITY WITH DIFFERENT ICN ARCHITECTURES

In the past few years, several ICN architectures have been proposed that provide different features and characteristics. It makes difficult to select a particular architecture with the given network conditions and characteristics. It can be partially addressed by establishing a common understanding of the different ICN architectures and compatibility should be a very important part, where different ICN architectures can be tested and compared to each other, while demonstrating their advantages. In addition, several upcoming technologies, such as IoT, machine/deep learning, and blockchain, etc should be considered in the future development of ICN.

B. ICN IN EDGE COMPUTING

Edge computing and ICN will be the most important technologies in 5G networks and beyond [57]. The edge computing paradigm brings computing resources, services and storage from the cloud to the edge of the network closer to the users, which leverages resources and reduces the response time of online services. However, edge computing methods (especially multi-access edge computing) are entirely based on host-oriented communication model (e.g. TCP/IP protocols). This leads to problems for data dissemination among highly mobile users and for addressing issues of Domain Name System (DNS) due to nodes continually joining or leaving the network [58].

In recent years, ICN has been proposed to shift the current host-oriented networking model towards an information-centric model. It relies on location independent naming, in-network caching, name-based routing and data self-security for effective content distribution across the whole network. This fact allows mobility support by nature [59]. Therefore, in order to overcome the above problems, ICN in edge computing is promising.

C. QUALITY OF SERVICE (QOS) SUPPORT AND 5G APPLICATION

So far, ICN is primarily working as a best effort framework. Low latency and high reliability are yet to be regarded as prerequisite for ICN operation. However, with increasing data traffic and stringent requirements of future applications (e.g., autonomous driving), the QoS requirement is becoming more and more important. Recently, Software Defined Network (SDN) [60], [61] technology proposed for VANET [62]–[64] can improve QoS provisioning. As ICN is a candidate network architecture to realize 5G objectives, SDN and NFV can provide an effective way to integrate ICN in 5G networks, without requiring to deploy new ICN hardware.

D. BUSINESS MODELS

A key aspect of ICN's success is the definition of incentives mechanisms to motivate users to process and forward data that they may not be interested in through caching. One possible approach is to reward users with monetary rewards or other services in return. The value of the incentive may be determined based on the degree of participation (e.g., the amount of forwarded/cached data), the quality of the provided resources (eg, the quality of the information may decrease according to the temporal/spatial scope). In general, agreements and business models are highly desirable among stakeholders.

VII. CONCLUSION

ICN research spans nearly a decade and its global standardization and research activities have been progressing at the moment. This article presented the history of global activities on ICN through the introduction to key documents developed in ITU-T and ICNRG.

ITU-T SG13 has led the future network standardization activities and published the following six Recommendations on ICN: Y.3033, Y.Sup35, Y.3071, Y.Sup47, Y.Sup48 and Y.3072. These Recommendations specify framework of data aware networking, scenarios and use cases, requirements and capabilities, standardization gaps and proof-of-concept, requirements and capabilities of name mapping and resolution for information-centric networking in IMT-2020. In parallel, ICNRG of the Internet Research Task Force has also developed and published three major documents: RFC 7927, RFC 7476, and RFC 7945. They provide ICN research community with common ground of research challenges, use-case scenarios, and evaluation approaches in the research of ICN.

The global cooperation to advance ICN is still in its early stage. ITU-T Recommendations and RFCs will form the foundation of subsequent global standardization and research cooperations and provide appropriate guidance to future ICN realization and development. Moreover, the future direction of ICN are also remarked based on the discussion from ICN standardizations status.

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