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Deployment Considerations for Information-Centric Networking (ICN)

Abstract

Information-Centric Networking (ICN) is now reaching technological maturity after many years of fundamental research and experimentation. This document provides a number of deployment considerations in the interest of helping the ICN community move forward to the next step of live deployments. First, the major deployment configurations for ICN are described, including the key overlay and underlay approaches. Then, proposed deployment migration paths are outlined to address major practical issues, such as network and application migration. Next, selected ICN trial experiences are summarized. Finally, protocol areas that require further standardization are identified to facilitate future interoperable ICN deployments. This document is a product of the Information-Centric Networking Research Group (ICNRG).

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Table of Contents

1. Introduction
2. Terminology
3. Abbreviations List
4. Deployment Configurations
 - 4.1. Clean-Slate ICN
 - 4.2. ICN-as-an-Overlay

- 4.3. ICN-as-an-Underlay
 - 4.3.1. Edge Network
 - 4.3.2. Core Network
 - 4.4. ICN-as-a-Slice
 - 4.5. Composite-ICN Approach
 - 5. Deployment Migration Paths
 - 5.1. Application and Service Migration
 - 5.2. Content Delivery Network Migration
 - 5.3. Edge Network Migration
 - 5.4. Core Network Migration
 - 6. Deployment Trial Experiences
 - 6.1. ICN-as-an-Overlay
 - 6.1.1. FP7 PURSUIT Efforts
 - 6.1.2. FP7 SAIL Trial
 - 6.1.3. NDN Testbed
 - 6.1.4. ICN2020 Efforts
 - 6.1.5. UMOBILE Efforts
 - 6.2. ICN-as-an-Underlay
 - 6.2.1. H2020 POINT and RIFE Efforts
 - 6.2.2. H2020 FLAME Efforts
 - 6.2.3. CableLabs Content Delivery System
 - 6.2.4. NDN IoT Trials
 - 6.2.5. NREN ICN Testbed
 - 6.2.6. DOCTOR Testbed
 - 6.3. Composite-ICN Approach
 - 6.4. Summary of Deployment Trials
 - 7. Deployment Issues Requiring Further Standardization
 - 7.1. Protocols for Application and Service Migration
 - 7.2. Protocols for Content Delivery Network Migration
 - 7.3. Protocols for Edge and Core Network Migration
 - 7.4. Summary of ICN Protocol Gaps and Potential Protocol Efforts
 - 8. Conclusion
 - 9. IANA Considerations
 - 10. Security Considerations
 - 11. Informative References
- Acknowledgments
 Authors' Addresses

1. Introduction

The ICNRC charter identifies deployment guidelines as an important topic area for the ICN community. Specifically, the charter states that defining concrete migration paths for ICN deployments that avoid forklift upgrades and defining practical ICN interworking configurations with the existing Internet paradigm are key topic areas that require further investigation [ICNRCCharter]. Also, it is well understood that results and conclusions from any mid- to large-scale ICN experiments in the live Internet will also provide useful guidance for deployments.

So far, outside of some preliminary investigations, such as [ICN-DEP-CON], there has not been much progress on this topic. This document attempts to fill some of these gaps by defining clear deployment configurations for ICN and associated migration pathways for these configurations. Also, selected deployment trial experiences of ICN technology are summarized. Recommendations are also made for potential future IETF standardization of key protocol functionality that will facilitate interoperable ICN deployments going forward.

The major configurations of possible ICN deployments are identified in this document as (1) Clean-slate ICN replacement of existing Internet infrastructure, (2) ICN-as-an-Overlay, (3) ICN-as-an-Underlay, (4) ICN-as-a-Slice, and (5) Composite-ICN. Existing ICN trial systems primarily fall under the ICN-as-an-Overlay, ICN-as-an-Underlay, and Composite-ICN configurations. Each of these deployment configurations have their respective strengths and weaknesses. This document will aim to provide guidance for current and future members of the ICN community when they consider deployment of ICN technologies.

This document represents the consensus of the Information-Centric Networking Research Group (ICNRG). It has been reviewed extensively by the Research Group (RG) members active in the specific areas of work covered by the document.

2. Terminology

This document assumes readers are, in general, familiar with the terms and concepts that are defined in [RFC7927] and [ICN-TERM]. In addition, this document defines the following terminology:

Deployment:

The final stage of the process of setting up an ICN network that is (1) ready for useful work (e.g., transmission of end-user video and text) in a live environment and (2) integrated and interoperable with the Internet. We consider the Internet in its widest sense where it encompasses various access networks (e.g., Wi-Fi or mobile radio network), service edge networks (e.g., for edge computing), transport networks, Content Distribution Networks (CDNs), core networks (e.g., mobile core network), and back-end processing networks (e.g., data centers). However, throughout this document, the discussion is typically limited to edge networks, core networks, and CDNs, for simplicity.

Information-Centric Networking (ICN):

A data-centric network architecture where accessing data by name is the essential network primitive. See [ICN-TERM] for further information.

Network Functions Virtualization (NFV):

A networking approach where network functions (e.g., firewalls or load balancers) are modularized as software logic that can run on general purpose hardware and, thus, are specifically decoupled from the previous generation of proprietary and dedicated hardware. See [RFC8568] for further information.

Software-Defined Networking (SDN):

A networking approach where the control and data planes for switches are separated, allowing for realizing capabilities, such as traffic isolation and programmable forwarding actions. See [RFC7426] for further information.

3. Abbreviations List

API:	Application Programming Interface
BIER:	Bit Index Explicit Replication
BoF:	Birds of a Feather (session)
CCNx:	Content-Centric Networking
CDN:	Content Distribution Network
CoAP:	Constrained Application Protocol
DASH:	Dynamic Adaptive Streaming over HTTP
Diffserv:	Differentiated Services
DoS:	Denial of Service
DTN:	Delay-Tolerant Networking
ETSI:	European Telecommunications Standards Institute
EU:	European Union
FP7:	7th Framework Programme for Research and Technological Development

HLS: HTTP Live Streaming

HTTP: HyperText Transfer Protocol

HTTPS: HyperText Transfer Protocol Secure

H2020: Horizon 2020 (research program)

ICN: Information-Centric Networking

ICNRG: Information-Centric Networking Research Group

IETF: Internet Engineering Task Force

IntServ: Integrated Services

IoT: Internet of Things

IP: Internet Protocol

IPv4: Internet Protocol Version 4

IPv6: Internet Protocol Version 6

IPTV: Internet Protocol Television

IS-IS: Intermediate System to Intermediate System

ISP: Internet Service Provider

k: kilo (1000)

L2: Layer 2

LTE: Long Term Evolution (or 4th generation cellular system)

MANO: Management and Orchestration

MEC: Multi-access Edge Computing

Mbps: Megabits per second

M2M: Machine-to-Machine

NAP: Network Attachment Point

NDN: Named Data Networking

NETCONF: Network Configuration Protocol

NetInf: Network of Information

NFD: Named Data Networking Forwarding Daemon

NFV: Network Functions Virtualization

NICT: Japan's National Institute of Information and Communications Technology

NR: New Radio (access network for 5G)

OAM: Operations, Administration, and Maintenance

ONAP: Open Network Automation Platform

OSPF: Open Shortest Path First

PoC: Proof of Concept (demo)

POINT: IP Over ICN - the better IP (project)

qMp: Quick Mesh Project
QoS: Quality of Service
RAM: Random Access Memory
RAN: Radio Access Network
REST: Representational State Transfer (architecture)
RESTCONF: Representational State Transfer Configuration (protocol)
RIFE: Architecture for an Internet For Everybody (project)
RIP: Routing Information Protocol
ROM: Read-Only Memory
RSVP: Resource Reservation Protocol
RTP: Real-time Transport Protocol
SDN: Software-Defined Networking
SFC: Service Function Chaining
SLA: Service Level Agreement
TCL: Transport Convergence Layer
TCP: Transmission Control Protocol
UDP: User Datagram Protocol
UMOBILE: Universal Mobile-centric and Opportunistic
Communications Architecture
US: United States
USA: United States of America
VoD: Video on Demand
VPN: Virtual Private Network
WG: Working Group
YANG: Yet Another Next Generation (data modeling language)
5G: Fifth Generation (cellular network)
6LoWPAN: IPv6 over Low-Power Wireless Personal Area Networks

4. Deployment Configurations

In this section, we present various deployment options for ICN. These are presented as "configurations" that allow for studying these options further. While this document will outline experiences with a number of these configurations (in Section 6), we will not provide an in-depth technical or commercial evaluation for any of them -- for this, we refer to existing literature in this space, such as [Tateson].

4.1. Clean-Slate ICN

ICN has often been described as a "clean-slate" approach with the goal to renew or replace the complete IP infrastructure of the Internet. As such, existing routing hardware and ancillary services, such as existing applications that are typically tied directly to the TCP/IP stack, are not taken for granted. For instance, a Clean-slate ICN deployment would see existing IP routers being replaced by ICN-

specific forwarding and routing elements, such as NFD [NFD], CCNx routers [Jacobson], or Publish-Subscribe Internet Technology (PURSUIT) forwarding nodes [IEEE_Communications].

While such clean-slate replacement could be seen as exclusive for ICN deployments, some ICN approaches (e.g., [POINT]) also rely on the deployment of general infrastructure upgrades, in this case, SDN switches. Different proposals have been made for various ICN approaches to enable the operation over an SDN transport [Reed] [CONET] [C_FLOW].

4.2. ICN-as-an-Overlay

Similar to other significant changes to the Internet routing fabric, particularly the transition from IPv4 to IPv6 or the introduction of IP multicast, this deployment configuration foresees the creation of an ICN overlay. Note that this overlay approach is sometimes, informally, also referred to as a tunneling approach. The overlay approach can be implemented directly (e.g., ICN-over-UDP), as described in [CCNx_UDP]. Alternatively, the overlay can be accomplished via ICN-in-L2-in-IP as in [IEEE_Communications], which describes a recursive layering process. Another approach used in the Network of Information (NetInf) is to define a convergence layer to map NetInf semantics to HTTP [NetInf]. Finally, [Overlay_ICN] describes an incremental approach to deploying an ICN architecture particularly well suited to SDN-based networks by also segregating ICN user- and control-plane traffic.

However, regardless of the flavor, the overlay approach results in islands of ICN deployments over existing IP-based infrastructure. Furthermore, these ICN islands are typically connected to each other via ICN/IP tunnels. In certain scenarios, this requires interoperability between existing IP routing protocols (e.g., OSPF, RIP, or IS-IS) and ICN-based ones. ICN-as-an-Overlay can be deployed over the IP infrastructure in either edge or core networks. This overlay approach is thus very attractive for ICN experimentation and testing, as it allows rapid and easy deployment of ICN over existing IP networks.

4.3. ICN-as-an-Underlay

Proposals, such as [POINT] and [White], outline the deployment option of using an ICN underlay that would integrate with existing (external) IP-based networks by deploying application-layer gateways at appropriate locations. The main reasons for such a configuration option is the introduction of ICN technology in given islands (e.g., inside a CDN or edge IoT network) to reap the benefits of native ICN, in terms of underlying multicast delivery, mobility support, fast indirection due to location independence, in-network computing, and possibly more. The underlay approach thus results in islands of native ICN deployments that are connected to the rest of the Internet through protocol conversion gateways or proxies. Routing domains are strictly separated. Outside of the ICN island, normal IP routing protocols apply. Within the ICN island, ICN-based routing schemes apply. The gateways transfer the semantic content of the messages (i.e., IP packet payload) between the two routing domains.

4.3.1. Edge Network

Native ICN networks may be located at the edge of the network where the introduction of new network architectures and protocols is easier in so-called greenfield deployments. In this context, ICN is an attractive option for scenarios, such as IoT [ICN-IoT]. The integration with the current IP protocol suite takes place at an application gateway/proxy at the edge network boundary, e.g., translating incoming CoAP request/response transactions [RFC7252] into ICN message exchanges or vice versa.

The work in [VSER] positions ICN as an edge service gateway driven by a generalized ICN-based service orchestration system with its own compute and network virtualization controllers to manage an ICN

infrastructure. The platform also offers service discovery capabilities to enable user applications to discover appropriate ICN service gateways. To exemplify a scenario in a use case, the [VSER] platform shows the realization of a multi-party audio/video conferencing service over such an edge cloud deployment of ICN routers realized over commodity hardware platforms. This platform has also been extended to offer seamless mobility as a service that [VSER-Mob] features.

4.3.2. Core Network

In this suboption, a core network would utilize edge-based protocol mapping onto the native ICN underlay. For instance, [POINT] proposes to map HTTP transactions or some other IP-based transactions, such as CoAP, directly onto an ICN-based message exchange. This mapping is realized at the NAP, for example, in access points or customer premise equipment, which, in turn, provides a standard IP interface to existing user devices. Thus, the NAP provides the apparent perception of an IP-based core network toward any external peering network.

The work in [White] proposes a similar deployment configuration. There, the goal is to use ICN for content distribution within CDN server farms. Specifically, the protocol mapping is realized at the ingress of the server farm where the HTTP-based retrieval request is served, while the response is delivered through a suitable egress node translation.

4.4. ICN-as-a-Slice

The objective of network slicing [NGMN-5G] is to multiplex a general pool of compute, storage, and bandwidth resources among multiple service networks with exclusive SLA requirements on transport and compute-level QoS and security. This is enabled through NFV and SDN technology functions that enable functional decomposition (hence, modularity, independent scalability of control, and/or the user-plane functions), agility, and service-driven programmability. Network slicing is often associated with 5G but is clearly not limited to such systems. However, from a 5G perspective, the definition of slicing includes access networks enabling dynamic slicing of the spectrum resources among various services, hence naturally extending itself to end points and cloud resources across multiple domains, to offer end-to-end guarantees. Once instantiated, these slices could include a mix of connectivity services (e.g., LTE-as-a-service), Over-the-Top (OTT) services (e.g., VoD), or other IoT services through composition of a group of virtual and/or physical network functions at the control-, user-, and service-plane levels. Such a framework can also be used to realize ICN slices with its own control and forwarding plane, over which one or more end-user services can be delivered [NGMN-Network-Slicing].

The 5G next generation architecture [fiveG-23501] provides the flexibility to deploy the ICN-as-a-Slice over either the edge (RAN) or mobile core network; otherwise, the ICN-as-a-Slice may be deployed end to end. Further discussions on extending the architecture presented in [fiveG-23501] and the corresponding procedures in [fiveG-23502] to support ICN has been provided in [ICN-5GC]. The document elaborates on two possible approaches to enable ICN: (1) as an edge service using the local data network (LDN) feature in 5G using User Plane Function (UPF) classification functions to fast handover to the ICN forwarder and (2) as a native deployment using the non-IP Protocol Data Unit (PDU) support that would allow new network layer PDU to be handed over to ICN UPFs collocated with the Generation NodeB (gNB) functions without invoking any IP functions. While the former deployment would still rely on 3GPP-based mobility functions, the later would allow mobility to be handled natively by ICN. However, both these deployment modes should benefit from other ICN features, such as in-network caching and computing. Associated with this ICN user-plane enablement, control-plane extensions are also proposed leveraging 5th Generation Core Network (5GC)'s interface to other application functions (AFs) to allow new network

service-level programmability. Such a generalized network slicing framework should be able to offer service slices over both IP and ICN. Coupled with the view of ICN functions as being "service function chaining" [RFC7665], an ICN deployment within such a slice could also be realized within the emerging control plane that is targeted for adoption in future (e.g., 5G mobile) network deployments. Finally, it should be noted that ICN is not creating the network slice but instead that the slice is created to run a 5G-ICN instance [Ravindran].

At the level of the specific technologies involved, such as ONAP [ONAP] (which can be used to orchestrate slices), the 5G-ICN slice requires compatibility, for instance, at the level of the forwarding/data plane depending on if it is realized as an overlay or using programmable data planes. With SDN emerging for new network deployments, some ICN approaches will need to integrate as a data-plane forwarding function with SDN, as briefly discussed in Section 4.1. Further cross-domain ICN slices can also be realized using frameworks, such as [ONAP].

4.5. Composite-ICN Approach

Some deployments do not clearly correspond to any of the previously defined basic configurations of (1) Clean-slate ICN, (2) ICN-as-an-Overlay, (3) ICN-as-an-Underlay, and (4) ICN-as-a-Slice. Or, a deployment may contain a composite mixture of the properties of these basic configurations. For example, the Hybrid ICN [H-ICN_1] approach carries ICN names in existing IPv6 headers and does not have distinct gateways or tunnels connecting ICN islands or any other distinct feature identified in the previous basic configurations. So we categorize Hybrid ICN and other approaches that do not clearly correspond to one of the other basic configurations as a Composite-ICN approach.

5. Deployment Migration Paths

We now focus on the various migration paths that will have importance to the various stakeholders that are usually involved in the deployment of ICN networks. We can identify these stakeholders as:

- * application providers
- * ISPs and service providers, both as core and access network providers, as well as ICN network providers
- * CDN providers (due to the strong relation of the ICN proposition to content delivery)
- * end-device manufacturers and users

Our focus is on technological aspects of such migration. Economic or regulatory aspects, such as those studied in [Tateson], [Techno_Economic], and [Internet_Pricing], are left out of our discussion.

5.1. Application and Service Migration

The Internet supports a multitude of applications and services using the many protocols defined over the packet-level IP service. HTTP provides one convergence point for these services with many web development frameworks based on the semantics provided by it. In recent years, even services such as video delivery have been migrating from the traditional RTP-over-UDP delivery to the various HTTP-level streaming solutions, such as DASH [DASH] and others. Nonetheless, many non-HTTP services exist, all of which need consideration when migrating from the IP-based Internet to an ICN-based one.

The underlay deployment configuration option presented in Section 4.3 aims at providing some level of compatibility to the existing ecosystem through a proxy-based message flow mapping mechanism (e.g.,

mapping of existing HTTP/TCP/IP message flows to HTTP/ICN message flows). A related approach of mapping TCP/IP to TCP/ICN message flows is described in [Moiseenko]. Another approach described in [Marchal] uses HTTP/NDN gateways and focuses, in particular, on the right strategy to map HTTP to NDN to guarantee a high level of compatibility with HTTP while enabling an efficient caching of data in the ICN island. The choice of approach is a design decision based on how to configure the protocol stack. For example, the approach described in [Moiseenko] carries the TCP layer into the ICN underlay, while the [Marchal] approach terminates both HTTP and TCP at the edge of the ICN underlay and maps these functionalities onto existing ICN functionalities.

Alternatively, ICN-as-an-Overlay (Section 4.2) and ICN-as-a-Slice (Section 4.4) allow for the introduction of the full capabilities of ICN through new application/service interfaces, as well as operations in the network. With that, these approaches of deployment are likely to aim at introducing new application/services capitalizing on those ICN capabilities, such as in-network multicast and/or caching.

Finally, [ICN-LTE-4G] outlines a dual-stack end-user device approach that is applicable for all deployment configurations. Specifically, it introduces middleware layers (called the TCL) in the device that will dynamically adapt existing applications to either an underlying ICN protocol stack or standard IP protocol stack. This involves end device signaling with the network to determine which protocol stack instance and associated middleware adaptation layers to utilize for a given application transaction.

5.2. Content Delivery Network Migration

A significant number of services and applications are devoted to content delivery in some form, e.g., as video delivery, social media platforms, and many others. CDNs are deployed to assist these services through localizing the content requests and therefore reducing latency and possibly increasing utilization of available bandwidth, as well as reducing the load on origin servers. Similar to the previous subsection, the underlay deployment configuration presented in Section 4.3 aims at providing a migration path for existing CDNs. This is also highlighted in a BIER use-case document [BIER], specifically with potential benefits in terms of utilizing multicast in the delivery of content but also reducing load on origin and delegation servers. We return to this benefit in the trial experiences in Section 6.

5.3. Edge Network Migration

Edge networks often see the deployment of novel network-level technology, e.g., in the space of IoT. For many years, such IoT deployments have relied, and often still do, on proprietary protocols for reasons, such as increased efficiency, lack of standardization incentives, and others. Utilizing the underlay deployment configuration in Section 4.3.1, application gateways/proxies can integrate such edge deployments into IP-based services, e.g., utilizing CoAP-based [RFC7252] M2M platforms, such as oneM2M [oneM2M] or others.

Another area of increased edge network innovation is that of mobile (access) networks, particularly in the context of the 5G mobile networks. Network softwarization (using technologies like service orchestration frameworks leveraging NFV and SDN concepts) are now common in access networks and other network segments. Therefore, the ICN-as-a-Slice deployment configuration in Section 4.4 provides a suitable migration path for the integration of non-IP-based edge networks into the overall system by virtue of realizing the relevant (ICN) protocols in an access network slice.

With the advent of SDN and NFV capabilities, so-called campus or site-specific deployments could see the introduction of ICN islands at the edge for scenarios such as gaming or deployments based on Augmented Reality (AR) / Virtual Reality (VR), e.g., smart cities or

theme parks.

5.4. Core Network Migration

Migrating core networks of the Internet or mobile networks requires not only significant infrastructure renewal but also the fulfillment of the key performance requirements, particularly in terms of throughput. For those parts of the core network that would migrate to an SDN-based optical transport, the ICN-as-a-Slice deployment configuration in Section 4.4 would allow the introduction of native ICN solutions within slices. This would allow for isolating the ICN traffic while addressing the specific ICN performance benefits (such as in-network multicast or caching) and constraints (such as the need for specific network elements within such isolated slices). For ICN solutions that natively work on top of SDN, the underlay deployment configuration in Section 4.3.2 provides an additional migration path, preserving the IP-based services and applications at the edge of the network while realizing the core network routing through an ICN solution (possibly itself realized in a slice of the SDN transport network).

6. Deployment Trial Experiences

In this section, we will outline trial experiences, often conducted within collaborative project efforts. Our focus here is on the realization of the various deployment configurations identified in Section 4; therefore, we categorize the trial experiences according to these deployment configurations. While a large body of work exists at the simulation or emulation level, we specifically exclude these studies from our analysis to retain the focus on real-life experiences.

6.1. ICN-as-an-Overlay

6.1.1. FP7 PURSUIT Efforts

Although the FP7 PURSUIT [IEEE_Communications] efforts were generally positioned as a Clean-slate ICN replacement of IP (Section 4.1), the project realized its experimental testbed as an L2 VPN-based overlay between several European, US, and Asian sites, following the overlay deployment configuration presented in Section 4.2. Software-based forwarders were utilized for the ICN message exchange, while native ICN applications (e.g., for video transmissions) were showcased. At the height of the project efforts, about 70+ nodes were active in the (overlay) network with presentations given at several conferences, as well as to the ICNRG.

6.1.2. FP7 SAIL Trial

The Network of Information (NetInf) is the approach to ICN developed by the EU FP7 Scalable and Adaptive Internet Solutions (SAIL) project [SAIL]. NetInf provides both name-based forwarding with CCNx-like semantics and name resolution (for indirection and late binding). The NetInf architecture supports different deployment options through its convergence layer, such as using UDP, HTTP, and even DTN underlays. In its first prototypes and trials, NetInf was deployed mostly in an HTTP embedding and in a UDP overlay following the overlay deployment configuration in Section 4.2. [SAIL_Prototyping] describes several trials, including a stadium environment and a multi-site testbed, leveraging NetInf's routing hint approach for routing scalability [SAIL_Content_Delivery].

6.1.3. NDN Testbed

The Named Data Networking (NDN) is one of the research projects of the National Science Foundation (NSF) of the USA as part of the Future Internet Architecture (FIA) Program. The original NDN proposal was positioned as a Clean-slate ICN replacement of IP (Section 4.1). However, in several trials, NDN generally follows the overlay deployment configuration of Section 4.2 to connect institutions over the public Internet across several continents. The

use cases covered in the trials include real-time videoconferencing, geolocating, and interfacing to consumer applications. Typical trials involve up to 100 NDN-enabled nodes [NDN-testbed] [Jangam].

6.1.4. ICN2020 Efforts

ICN2020 is an ICN-related project of the EU H2020 research program and NICT [ICN2020-overview]. ICN2020 has a specific focus to advance ICN towards real-world deployments through applications, such as video delivery, interactive videos, and social networks. The federated testbed spans the USA, Europe, and Japan. Both NDN and CCNx approaches are within the scope of the project.

ICN2020 has released a set of interim public technical reports. The report [ICN2020-Experiments] contains a detailed description of the progress made in both local testbeds and federated testbeds. The plan for the federated testbed includes integrating the NDN testbed, the CUTEi testbed [RFC7945] [CUTEi], and the GEANT testbed [GEANT] to create an overlay deployment configuration of Section 4.2 over the public Internet. The total network contains 37 nodes. Since video was an important application, typical throughput was measured in certain scenarios and found to be in the order of 70 Mbps per node.

6.1.5. UMOBILE Efforts

UMOBILE is another of the ICN research projects under the H2020 research program [UMOBILE-overview]. The UMOBILE architecture integrates the principles of DTN and ICN in a common framework to support edge computing and mobile opportunistic wireless environments (e.g., post-disaster scenarios and remote areas). The UMOBILE architecture [UMOBILE-2] was developed on top of the NDN framework by following the overlay deployment configuration of Section 4.2. UMOBILE aims to extend Internet functionally by combining ICN and DTN technologies.

One of the key aspects of UMOBILE was the extension of the NDN framework to locate network services (e.g., mobility management and intermittent connectivity support) and user services (e.g., pervasive content management) as close as possible to the end users to optimize bandwidth utilization and resource management. Another aspect was the evolution of the NDN framework to operate in challenging wireless networks, namely in emergency scenarios [UMOBILE-3] and environments with intermittent connectivity. To achieve this, the NDN framework was leveraged with a new messaging application called Oi! [UMOBILE-4] [UMOBILE-5], which supports intermittent wireless networking. UMOBILE also implements a new data-centric wireless routing protocol, DABBER [UMOBILE-6] [DABBER], which was designed based on data reachability metrics that take availability of adjacent wireless nodes and different data sources into consideration. The contextual awareness of the wireless network operation is obtained via a machine-learning agent running within the wireless nodes [UMOBILE-7].

The consortium has completed several ICN deployment trials. In a post-disaster scenario trial [UMOBILE-8], a special DTN face was created to provide reachability to remote areas where there is no typical Internet connection. Another trial was the ICN deployment over the "Guifi.net" community network in the Barcelona region. This trial focused on the evaluation of an ICN edge computing platform, called PiCasso [UMOBILE-9]. In this trial, ten (10) Raspberry Pis were deployed across Barcelona to create an ICN overlay network on top of the existing IP routing protocol (e.g., qMp routing). This trial showed that ICN can play a key role in improving data delivery QoS and reducing the traffic in intermittent connectivity environments (e.g., wireless community network). A third trial in Italy was focused on displaying the capability of the UMOBILE architecture to reach disconnected areas and assist responsible authorities in emergencies, corresponding to an infrastructure scenario. The demonstration encompassed seven (7) end-user devices, one (1) access point, and one (1) gateway.

6.2. ICN-as-an-Underlay

6.2.1. H2020 POINT and RIFE Efforts

POINT and RIFE are two more ICN-related research projects of the H2020 research program. The efforts in the H2020 POINT and RIFE projects follow the underlay deployment configuration in Section 4.3.2; edge-based NAPs provide the IP/HTTP-level protocol mapping onto ICN protocol exchanges, while the SDN underlay (or the VPN-based L2 underlay) is used as a transport network.

The multicast and service endpoint surrogate benefit in HTTP-based scenarios, such as for HTTP-level streaming video delivery, and have been demonstrated in the deployed POINT testbed with 80+ nodes being utilized. Demonstrations of this capability have been given to the ICNRG, and public demonstrations were also provided at events [MWC_Demo]. The trial has also been accepted by the ETSI MEC group as a public proof-of-concept demonstration.

While the aforementioned demonstrations all use the overlay deployment, H2020 also has performed ICN underlay trials. One such trial involved commercial end users located in the PrimeTel network in Cyprus with the use case centered on IPTV and HLS video dissemination. Another trial was performed over the "Guifi.net" community network in the Barcelona region, where the solution was deployed in 40 households, providing general Internet connectivity to the residents. Standard IPTV Set-Top Boxes (STBs), as well as HLS video players, were utilized in accordance with the aim of this deployment configuration, namely to provide application and service migration.

6.2.2. H2020 FLAME Efforts

The H2020 Facility for Large-Scale Adaptive Media Experimentation (FLAME) efforts concentrate on providing an experimental ground for the aforementioned POINT/RIFE solution in initially two city-scale locations, namely in Bristol and Barcelona. This trial followed the underlay deployment configuration in Section 4.3.2, as per the POINT/RIFE approach. Experiments were conducted with the city/university joint venture Bristol-is-Open (BIO) to ensure the readiness of the city-scale SDN transport network for such experiments. Another trial was for the ETSI MEC PoC. This trial showcased operational benefits provided by the ICN underlay for the scenario of a location-based game. These benefits aim at reduced network utilization through improved video delivery performance (multicast of all captured videos to the service surrogates deployed in the city at six locations), as well as reduced latency through the play out of the video originating from the local NAP, collocated with the Wi-Fi Access Point (AP) instead of a remote server, i.e., the playout latency was bounded by the maximum single-hop latency.

Twenty three (23) large-scale media service experiments are planned as part of the H2020 FLAME efforts in the area of Future Media Internet (FMI). The platform, which includes the ICN capabilities, integrated with NFV and SDN capabilities of the infrastructure. The ultimate goal of these platform efforts is the full integration of ICN into the overall media function platform for the provisioning of advanced (media-centric) Internet services.

6.2.3. CableLabs Content Delivery System

The CableLabs ICN work reported in [White] proposes an underlay deployment configuration based on Section 4.3.2. The use case is ICN for content distribution within complex CDN server farms to leverage ICN's superior in-network caching properties. This CDN based on "island of ICN" is then used to service standard HTTP/IP-based content retrieval requests coming from the general Internet. This approach acknowledges that whole scale replacement (see Section 4.1) of existing HTTP/IP end-user applications and related web infrastructure is a difficult proposition. [White] is clear that the architecture proposed has not yet been tested experimentally but that

implementations are in process and expected in the 3-5 year time frame.

6.2.4. NDN IoT Trials

[Baccelli] summarizes the trial of an NDN system adapted specifically for a wireless IoT scenario. The trial was run with 60 nodes distributed over several multistory buildings in a university campus environment. The NDN protocols were optimized to run directly over 6LoWPAN wireless link layers. The performance of the NDN-based IoT system was then compared to an equivalent system running standard IP-based IoT protocols. It was found that the NDN-based IoT system was superior in several respects, including in terms of energy consumption and for RAM and ROM footprints [Baccelli] [Anastasiades]. For example, the binary file size reductions for NDN protocol stack versus standard IP-based IoT protocol stack on given devices were up to 60% less for ROM size and up to 80% less for RAM size.

6.2.5. NREN ICN Testbed

The National Research and Education Network (NREN) ICN Testbed is a project sponsored by Cisco, Internet2, and the US Research and Education community. Participants include universities and US federal government entities that connect via a nationwide VPN-based L2 underlay. The testbed uses the CCNx approach and is based on the [CICN] open-source software. There are approximately 15 nodes spread across the USA that connect to the testbed. The project's current focus is to advance data-intensive science and network research by improving data movement, searchability, and accessibility.

6.2.6. DOCTOR Testbed

The DOCTOR project is a French research project meaning "Deployment and Securitisation of new Functionalities in Virtualized Networking Environments". The project aims to run NDN over virtualized NFV infrastructure [Doctor] (based on Docker technology) and focuses on the NFV MANO aspects to build an operational NDN network focusing on important performance criteria, such as security, performance, and interoperability.

The data plane relies on an HTTP/NDN gateway [Marchal] that processes HTTP traffic and transports it in an optimized way over NDN to benefit from the properties of the NDN island (i.e., by mapping HTTP semantics to NDN semantics within the NDN island). The testbed carries real Web traffic of users and has been currently evaluated with the top 1000 most popular websites. The users only need to set the gateway as the web proxy. The control plane relies on a central manager that uses machine-learning-based detection methods [Mai-1] from the data gathered by distributed probes and applies orchestrated countermeasures against NDN attacks [Nguyen-1] [Nguyen-2] [Mai-2] or performance issues. A remediation can be, for example, the scale up of a bottleneck component or the deployment of a security function, like a firewall or a signature verification module. Test results thus far have indicated that key attacks can be detected accurately. For example, content poisoning attacks can be detected at up to over 95% accuracy (with less than 0.01% false positives) [Nguyen-3].

6.3. Composite-ICN Approach

Hybrid ICN [H-ICN_1] [H-ICN_2] is an approach where the ICN names are mapped to IPv6 addresses and other ICN information is carried as payload inside the IP packet. This allows standard (ICN-unaware) IP routers to forward packets based on IPv6 info but enables ICN-aware routers to apply ICN semantics. The intent is to enable rapid hybrid deployments and seamless interconnection of IP and Hybrid ICN domains. Hybrid ICN uses [CICN] open-source software. Initial tests have been done with 150 clients consuming DASH videos, which showed good scalability properties at the server side using the Hybrid ICN transport [H-ICN_3] [H-ICN_2].

6.4. Summary of Deployment Trials

In summary, there have been significant trials over the years with all the major ICN protocol flavors (e.g., CCNx, NDN, and POINT) using both the ICN-as-an-Overlay and ICN-as-an-Underlay deployment configurations. The major limitations of the trials include the fact that only a limited number of applications have been tested. However, the tested applications include both native ICN and existing IP-based applications (e.g., videoconferencing and IPTV). Another limitation of the trials is that all of them involve less than 1k users.

Huawei and China Unicom have just started trials of the ICN-as-a-Slice configuration to demonstrate ICN features of security, mobility, and bandwidth efficiency over a wired infrastructure using videoconferencing as the application scenario [Chakraborti]; also, this prototype has been extended to demonstrate this over a 5G-NR access.

The Clean-slate ICN approach has obviously never been in trials, as complete replacement of Internet infrastructure (e.g., existing applications, TCP/IP protocol stack, IP routers, etc.) is no longer considered a viable alternative.

Finally, Hybrid ICN is a Composite-ICN approach that offers an interesting alternative, as it allows ICN semantics to be embedded in standard IPv6 packets so the packets can be routed through either IP routers or Hybrid ICN routers. Note that some other trials, such as the DOCTOR testbed (Section 6.2.6), could also be characterized as a Composite-ICN approach, because it contains both ICN gateways (as in ICN-as-an-Underlay) and virtualized infrastructure (as in ICN-as-a-Slice). However, for the DOCTOR testbed, we have chosen to characterize it as an ICN-as-an-Underlay configuration because that is a dominant characteristic.

7. Deployment Issues Requiring Further Standardization

"Information-Centric Networking (ICN) Research Challenges" [RFC7927] describes key ICN principles and technical research topics. As the title suggests, [RFC7927] is research oriented without a specific focus on deployment or standardization issues. This section addresses this open area by identifying key protocol functionality that may be relevant for further standardization effort in the IETF. The focus is specifically on identifying protocols that will facilitate future interoperable ICN deployments correlating to the scenarios identified in the deployment migration paths in Section 5. The identified list of potential protocol functionality is not exhaustive.

7.1. Protocols for Application and Service Migration

End-user applications and services need a standardized approach to trigger ICN transactions. For example, in Internet and web applications today, there are established socket APIs, communication paradigms (such as REST), common libraries, and best practices. We see a need to study application requirements in an ICN environment further and, at the same time, develop new APIs and best practices that can take advantage of ICN communication characteristics.

7.2. Protocols for Content Delivery Network Migration

A key issue in CDNs is to quickly find a location of a copy of the object requested by an end user. In ICN, a Named Data Object (NDO) is typically defined by its name. [RFC6920] defines a mechanism that is suitable for static naming of ICN data objects. Other ways of encoding and representing ICN names have been described in [RFC8609] and [RFC8569]. Naming dynamically generated data requires different approaches (e.g., hash-digest-based names would normally not work), and there is a lack of established conventions and standards.

Another CDN issue for ICN is related to multicast distribution of content. Existing CDNs have started using multicast mechanisms for

certain cases, such as for broadcasting streaming TV. However, as discussed in Section 6.2.1, certain ICN approaches provide substantial improvements over IP multicast, such as the implicit support for multicast retrieval of content in all ICN flavors.

Caching is an implicit feature in many ICN architectures that can improve performance and availability in several scenarios. The ICN in-network caching can augment managed CDN and improve its performance. The details of the interplay between ICN caching and managed CDN need further consideration.

7.3. Protocols for Edge and Core Network Migration

ICN provides the potential to redesign current edge and core network computing approaches. Leveraging ICN's inherent security and its ability to make name data and dynamic computation results available independent of location can enable a lightweight insertion of traffic into the network without relying on redirection of DNS requests. For this, proxies that translate from commonly used protocols in the general Internet to ICN message exchanges in the ICN domain could be used for the migration of application and services within deployments at the network edge but also in core networks. This is similar to existing approaches for IoT scenarios where a proxy translates CoAP request/responses to other message formats. For example, [RFC8075] specifies proxy mapping between CoAP and HTTP protocols. Also, [RFC8613] is an example of how to pass end-to-end encrypted content between HTTP and CoAP by an application-layer security mechanism. Further work is required to identify if an approach like [RFC8613], or some other approach, is suitable to preserve ICN message security through future protocol translation functions of gateways/proxies.

Interaction and interoperability between existing IP routing protocols (e.g., OSPF, RIP, or IS-IS) and ICN routing approaches (e.g., NFD and CCNx routers) are expected, especially in the overlay approach. Another important topic is the integration of ICN into networks that support virtualized infrastructure in the form of NFV/SDN and most likely utilize SFC as a key protocol. Further work is required to validate this idea and document best practices.

There are several existing approaches to supporting QoS in IP networks, including Diffserv, IntServ, and RSVP. Some initial ideas for QoS support in ICN networks are outlined in [FLOW-CLASS], which proposes an approach based on flow classification to enable functions, such as ICN rate control and cache control. Also, [ICN-QoS] proposes how to use Diffserv Differentiated Services Code Point (DSCP) codes to support QoS for ICN-based data path delivery. Further work is required to identify the best approaches for support of QoS in ICN networks.

OAM is a crucial area that has not yet been fully addressed by the ICN research community but which is obviously critical for future deployments of ICN. Potential areas that need investigation include whether the YANG data modeling approach and associated NETCONF/RESTCONF protocols need any specific updates for ICN support. Another open area is how to measure and benchmark performance of ICN networks comparable to the sophisticated techniques that exist for standard IP networks, virtualized networks, and data centers. It should be noted that some initial progress has been made in the area of ICN network path traceroute facility with approaches, such as CCNxinfo [CNNinfo] [Contrace].

7.4. Summary of ICN Protocol Gaps and Potential Protocol Efforts

Without claiming completeness, Table 1 maps the open ICN issues identified in this document to potential protocol efforts that could address some aspects of the gap.

ICN Gap	Potential Protocol Effort
1-Support of	HTTP/CoAP support of ICN semantics

REST APIs	
2-Naming	Dynamic naming of ICN data objects
3-Routing	Interactions between IP and ICN routing protocols
4-Multicast distribution	Multicast enhancements for ICN
5-In-network caching	ICN cache placement and sharing
6-NFV/SDN support	Integration of ICN with NFV/SDN and including possible impacts to SFC
7-ICN mapping	Mapping of HTTP and other protocols onto ICN message exchanges (and vice versa) while preserving ICN message security
8-QoS support	Support of ICN QoS via mechanisms, such as Diffserv and flow classification
9-OAM support	YANG data models, NETCONF/RESTCONF protocols, and network-performance measurements

Table1: Mapping of ICN Gaps to Potential Protocol Efforts

8. Conclusion

This document provides high-level deployment considerations for current and future members of the ICN community. Specifically, the major configurations of possible ICN deployments are identified as (1) Clean-slate ICN replacement of existing Internet infrastructure, (2) ICN-as-an-Overlay, (3) ICN-as-an-Underlay, (4) ICN-as-a-Slice, and (5) Composite-ICN. Existing ICN trial systems primarily fall under the ICN-as-an-Overlay, ICN-as-an-Underlay, and Composite-ICN configurations.

In terms of deployment migration paths, ICN-as-an-Underlay offers a clear migration path for CDN, edge, or core networks to go to an ICN paradigm (e.g., for an IoT deployment) while leaving the critical mass of existing end-user applications untouched. ICN-as-an-Overlay is the easiest configuration to deploy rapidly, as it leaves the underlying IP infrastructure essentially untouched. However, its applicability for general deployment must be considered on a case-by-case basis. (That is, can it support all required user applications?). ICN-as-a-Slice is an attractive deployment option for upcoming 5G systems (i.e., for 5G radio and core networks) that will naturally support network slicing, but this still has to be validated through more trial experiences. Composite-ICN, by its nature, can combine some of the best characteristics of the other configurations, but its applicability for general deployment must again be considered on a case-by-case basis (i.e., can enough IP routers be upgraded to support Composite-ICN functionality to provide sufficient performance benefits?).

There has been significant trial experience with all the major ICN protocol flavors (e.g., CCNx, NDN, and POINT). However, only a limited number of applications have been tested so far, and the maximum number of users in any given trial has been less than 1k users. It is recommended that future ICN deployments scale their users gradually and closely monitor network performance as they go above 1k users. A logical approach would be to increase the number of users in a slowly increasing linear manner and monitor network performance and stability, especially at every multiple of 1k users.

Finally, this document describes a set of technical features in ICN that warrant potential future IETF specification work. This will aid

initial and incremental deployments to proceed in an interoperable manner. The fundamental details of the potential protocol specification effort, however, are best left for future study by the appropriate IETF WGs and/or BoFs. The ICNRG can aid this process in the near and mid-term by continuing to examine key system issues like QoS mechanisms, flexible naming schemes, and OAM support for ICN.

9. IANA Considerations

This document has no IANA actions.

10. Security Considerations

ICN was purposefully designed from the start to have certain intrinsic security properties. The most well known of which are authentication of delivered content and (optional) encryption of the content. [RFC7945] has an extensive discussion of various aspects of ICN security, including many that are relevant to deployments. Specifically, [RFC7945] points out that ICN access control, privacy, security of in-network caches, and protection against various network attacks (e.g., DoS) have not yet been fully developed due to the lack of a sufficient mass of deployments. [RFC7945] also points out relevant advances occurring in the ICN research community that hold promise to address each of the identified security gaps. Lastly, [RFC7945] points out that as secure communications in the existing Internet (e.g., HTTPS) become the norm, major gaps in ICN security will inevitably slow down the adoption of ICN.

In addition to the security findings of [RFC7945], this document has highlighted that all anticipated ICN deployment configurations will involve coexistence with existing Internet infrastructure and applications. Thus, even the basic authentication and encryption properties of ICN content will need to account for interworking with non-ICN content to preserve end-to-end security. For example, in the edge network underlay deployment configuration described in Section 4.3.1, the gateway/proxy that translates HTTP or CoAP request/responses into ICN message exchanges will need to support a security model to preserve end-to-end security. One alternative would be to consider an approach similar to [RFC8613], which is used to pass end-to-end encrypted content between HTTP and CoAP by an application-layer security mechanism. Further investigation is required to see if this approach is suitable to preserve ICN message security through future protocol translation functions (e.g., ICN to HTTP or CoAP to ICN) of gateways/proxies.

Finally, the DOCTOR project discussed in Section 6.2.6 is an example of an early deployment that is looking at specific attacks against ICN infrastructure, in this case, looking at Interest Flooding Attacks [Nguyen-2] and Content Poisoning Attacks [Nguyen-1] [Mai-2] [Nguyen-3] and evaluating potential countermeasures based on MANO-orchestrated actions on the virtualized infrastructure [Mai-1].

11. Informative References

[Anastasiades]

Anastasiades, C., "Information-centric communication in mobile and wireless networks", PhD Dissertation, DOI 10.7892/boris.83683, June 2016, <http://boris.unibe.ch/83683/1/16anastasiades_c.pdf>.

[Baccelli] Baccelli, E., et al., "Information Centric Networking in the IoT: Experiments with NDN in the Wild", ACM-ICN '14: Proceedings of the 1st ACM Conference on Information-Centric Networking, DOI 10.1145/2660129.2660144, September 2014, <<http://conferences2.sigcomm.org/acm-icn/2014/papers/p77.pdf>>.

[BIER] Trossen, D., Rahman, A., Wang, C., and T. Eckert, "Applicability of BIER Multicast Overlay for Adaptive Streaming Services", Work in Progress, Internet-Draft, draft-ietf-bier-multicast-http-response-03, 4 February

2020, <<https://tools.ietf.org/html/draft-ietf-bier-multicast-http-response-03>>.

- [CCNx_UDP] PARC, "CCNx Over UDP", <<https://www.ietf.org/proceedings/interim-2015-icnrg-04/slides/slides-interim-2015-icnrg-4-5.pdf>>.
- [Chakraborti]
Chakraborti, A., et al., "Design and Evaluation of a Multi-source Multi-destination Real-time Application on Content Centric Network", 2018 1st IEEE International Conference on Hot Information-Centric Networking (HotICN), DOI 10.1109/HOTICN.2018.8605980, August 2018, <<https://doi.org/10.1109/HOTICN.2018.8605980>>.
- [CICN] fd.io, "Cicn", <<https://wiki.fd.io/view/Cicn>>.
- [CNNinfo] Asaeda, H., Ooka, A., and X. Shao, "CCNinfo: Discovering Content and Network Information in Content-Centric Networks", Work in Progress, Internet-Draft, draft-irtf-icnrg-ccninfo-04, 22 March 2020, <<https://tools.ietf.org/html/draft-irtf-icnrg-ccninfo-04>>.
- [CONET] Veltri, L., et al., "Supporting Information-Centric Functionality in Software Defined Networks", 2012 IEEE International Conference on Communications (ICC), DOI 10.1109/ICC.2012.6364916, November 2012, <http://netgroup.uniroma2.it/Stefano_Salsano/papers/salsano-iccl2-wshop-sdn.pdf>.
- [Contrace] Asaeda, H., et al., "Contrace: a tool for measuring and tracing content-centric networks", IEEE Communications Magazine, Volume 53, Issue 3, DOI 10.1109/MCOM.2015.7060502, March 2015, <<https://doi.org/10.1109/MCOM.2015.7060502>>.
- [CUTEi] Asaeda, H., Li, R., and N. Choi, "Container-Based Unified Testbed for Information Centric Networking", IEEE Network Volume 28, Issue:6, DOI 10.1109/MNET.2014.6963806, November 2014, <<https://doi.org/10.1109/MNET.2014.6963806>>.
- [C_FLOW] D. Chang, et al., "C_flow: An efficient content delivery framework with OpenFlow", The International Conference on Information Networking 2014 (ICOIN2014), pp. 270-275, DOI 10.1109/ICOIN.2014.6799480, February 2014, <<https://ieeexplore.ieee.org/document/6799480>>.
- [DABBER] Mendes, P., Sofia, R., Tsaoussidis, V., and C. Borrego, "Information-centric Routing for Opportunistic Wireless Networks", Work in Progress, Internet-Draft, draft-mendes-icnrg-dabber-04, 14 March 2020, <<https://tools.ietf.org/html/draft-mendes-icnrg-dabber-04>>.
- [DASH] DASH, "DASH Industry Forum", <<http://dashif.org/>>.
- [Doctor] DOCTOR, "Deployment and securisation of new functionalities in virtualized networking environments", <<http://www.doctor-project.org/index.htm>>.
- [fiveG-23501]
3GPP, "System Architecture for the 5G System", Release 15, 3GPP TS 23.501, December 2017.
- [fiveG-23502]
3GPP, "Procedures for the 5G System (5GS)", Release 15, 3GPP TS 23.502.
- [FLOW-CLASS]
Moiseenko, I. and D. Oran, "Flow Classification in

Information Centric Networking", Work in Progress, Internet-Draft, draft-moiseenko-icnrg-flowclass-05, 20 January 2020, <<https://tools.ietf.org/html/draft-moiseenko-icnrg-flowclass-05>>.

- [GEANT] GEANT, "GEANT", <<https://www.geant.org/>>.
- [H-ICN_1] Cisco, "Cisco Announces Important Steps toward Adoption of Information-Centric Networking", February 2017, <<http://blogs.cisco.com/sp/cisco-announces-important-steps-toward-adoption-of-information-centric-networking>>.
- [H-ICN_2] Cisco, "Mobile Video Delivery with Hybrid ICN: IP-integrated ICN Solution for 5G", <<https://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/ultra-services-platform/mwcl7-hicn-video-wp.pdf>>.
- [H-ICN_3] Muscariello, L., et al, "Hybrid Information-Centric Networking: ICN inside the Internet Protocol", ICNRG Interim Meeting, March 2018, <<https://datatracker.ietf.org/meeting/interim-2018-icnrg-01/materials/slides-interim-2018-icnrg-01-sessa-hybrid-icn-hicn-luca-muscariello>>.
- [ICN-5GC] Ravindran, R., Suthar, P., Trossen, D., Wang, C., and G. White, "Enabling ICN in 3GPP's 5G NextGen Core Architecture", Work in Progress, Internet-Draft, draft-ravi-icnrg-5gc-icn-04, 31 May 2019, <<https://tools.ietf.org/html/draft-ravi-icnrg-5gc-icn-04>>.
- [ICN-DEP-CON] Paik, E., Yun, W., Kwon, T., and H. Choi, "Deployment Considerations for Information-Centric Networking", Work in Progress, Internet-Draft, draft-paik-icn-deployment-considerations-00, 15 July 2013, <<https://tools.ietf.org/html/draft-paik-icn-deployment-considerations-00>>.
- [ICN-IoT] Ravindran, R., Zhang, Y., Grieco, L., Lindgren, A., Burke, J., Ahlgren, B., and A. Azgin, "Design Considerations for Applying ICN to IoT", Work in Progress, Internet-Draft, draft-irtf-icnrg-icniot-03, 2 May 2019, <<https://tools.ietf.org/html/draft-irtf-icnrg-icniot-03>>.
- [ICN-LTE-4G] Suthar, P., Stolic, M., Jangam, A., Ed., Trossen, D., and R. Ravindran, "Native Deployment of ICN in LTE, 4G Mobile Networks", Work in Progress, Internet-Draft, draft-irtf-icnrg-icn-lte-4g-05, 4 November 2019, <<https://tools.ietf.org/html/draft-irtf-icnrg-icn-lte-4g-05>>.
- [ICN-QoS] Jangam, A., Suthar, P., and M. Stolic, "Supporting QoS aware Data Delivery in Information Centric Networks", Work in Progress, Internet-Draft, draft-anilj-icnrg-icn-qos-00, 14 July 2018, <<https://tools.ietf.org/html/draft-anilj-icnrg-icn-qos-00>>.
- [ICN-TERM] Wissingh, B., Wood, C., Afanasyev, A., Zhang, L., Oran, D., and C. Tschudin, "Information-Centric Networking (ICN): CCNx and NDN Terminology", Work in Progress, Internet-Draft, draft-irtf-icnrg-terminology-08, 17 January 2020, <<https://tools.ietf.org/html/draft-irtf-icnrg-terminology-08>>.
- [ICN2020-Experiments] ICN2020, "D4.1: 1st Yearly WP4 Report & Demonstration", August 2017, <<https://projects.gwdg.de/attachments/6840/D4.1-PU.pdf>>.

- [ICN2020-overview] ICN2020, "ICN2020 Project Overview", <<http://www.icn2020.org/>>.
- [ICNRGCharter] IRTF, "Information-Centric Networking Research Group Charter", <<https://datatracker.ietf.org/doc/charter-irtf-icnrg/>>.
- [IEEE_Communications] Trossen, D. and G. Parisis, "Designing and realizing an information-centric internet", IEEE Communications Magazine, Volume 50, Issue 7, DOI 10.1109/MCOM.2012.6231280, <<https://doi.org/10.1109/MCOM.2012.6231280>>.
- [Internet_Pricing] Trossen, D. and G. Biczok, "Not paying the truck driver: differentiated pricing for the future internet", ReARCH '10: Proceedings of the Re-Architecting the Internet Workshop, ReArch '10: Proceedings of the Re-Architecting the Internet Workshop, DOI 10.1145/1921233.1921235, November 2010, <<https://doi.org/10.1145/1921233.1921235>>.
- [Jacobson] Jacobson, V., et al., "Networking Named Content", CoNEXT '09: Proceedings of the 5th international conference on Emerging networking experiments and technologies, DOI 10.1145/1658939.1658941, December 2009, <<https://doi.org/10.1145/1658939.1658941>>.
- [Jangam] Jangam, A., et al., "nlsrcSIM: Porting and Simulation of Named-data Link State Routing Protocol into ndnSIM", DIVANet '17: Proceedings of the 6th ACM Symposium on Development and Analysis of Intelligent Vehicular Networks and Applications, DOI 10.1145/3132340.3132351, November 2017, <<https://dl.acm.org/citation.cfm?id=3132351>>.
- [Mai-1] Mai, H., et al., "Implementation of content poisoning attack detection and reaction in virtualized NDN networks", 2018 21st Conference on Innovation in Clouds, Internet and Networks and Workshops (ICIN), DOI 10.1109/ICIN.2018.8401591, July 2018, <<https://ieeexplore.ieee.org/document/8401591>>.
- [Mai-2] Mai, H., et al., "Towards a Security Monitoring Plane for Named Data Networking: Application to Content Poisoning Attack", NOMS 2018 - 2018 IEEE/IFIP Network Operations Management Symposium, DOI 10.1109/NOMS.2018.8406246, July 2018, <<https://doi.org/10.1109/NOMS.2018.8406246>>.
- [Marchal] Marchal, X., et al., "Leveraging NFV for the Deployment of NDN: Application to HTTP Traffic Transport", NOMS 2018 - 2018 IEEE/IFIP Network Operations and Management Symposium, DOI 10.1109/NOMS.2018.8406206, July 2018, <<http://www.mallouli.com/recherche/publications/noms2018-1.pdf>>.
- [Moiseenko] Moiseenko, I. and D. Oran, "TCP/ICN: Carrying TCP over Content Centric and Named Data Networks", ACM-ICN '16: Proceedings of the 3rd ACM Conference on Information-Centric Networking, DOI 10.1145/2984356.2984357, September 2016, <<http://conferences2.sigcomm.org/acm-icn/2016/proceedings/p112-moiseenko.pdf>>.
- [MWC_Demo] InterDigital, "InterDigital Demo at Mobile World Congress (MWC)", 2016, <<http://www.interdigital.com/download/56d5c71bd616f892ba001861>>.
- [NDN-testbed] NDN, "NDN Testbed", <<https://named-data.net/ndn-testbed/>>.

- [NetInf] Kutscher, D., Farrell, S., and E. Davies, "The NetInf Protocol", Work in Progress, Internet-Draft, draft-kutscher-icnrg-netinf-01, 10 February 2013, <<https://tools.ietf.org/html/draft-kutscher-icnrg-netinf-01>>.
- [NFD] NDN, "NFD - Named Data Networking Forwarding Daemon", <<https://named-data.net/doc/NFD/current/>>.
- [NGMN-5G] NGMN Alliance, "5G White Paper", February 2015, <https://www.ngmn.org/wp-content/uploads/NGMN_5G_White_Paper_V1_0.pdf>.
- [NGMN-Network-Slicing] NGMN Alliance, "Description of Network Slicing Concept", NGMN 5G P1, Requirements & Architecture, Work Stream End-to-End Architecture, Version 1.0, January 2016, <https://www.ngmn.org/wp-content/uploads/160113_NGMN_Network_Slicing_v1_0.pdf>.
- [Nguyen-1] Nguyen, T., et al., "Content Poisoning in Named Data Networking: Comprehensive characterization of real deployment", 2017 IFIP/IEEE Symposium on Integrated Network and Service Management (IM), DOI 10.23919/INM.2017.7987266, July 2017, <<https://doi.org/10.23919/INM.2017.7987266>>.
- [Nguyen-2] Nguyen, T., Cogramne, R., and G. Doyen, "An optimal statistical test for robust detection against interest flooding attacks in CCN", 2015 IFIP/IEEE International Symposium on Integrated Network Management (IM), DOI 10.1109/INM.2015.7140299, July 2015, <<https://doi.org/10.1109/INM.2015.7140299>>.
- [Nguyen-3] Nguyen, T., et al., "A Security Monitoring Plane for Named Data Networking Deployment", IEEE Communications Magazine, Volume: 56, Issue 11, DOI 10.1109/MCOM.2018.1701135, November 2018, <<https://doi.org/10.1109/MCOM.2018.1701135>>.
- [ONAP] ONAP, "Open Network Automation Platform", <<https://www.onap.org/>>.
- [oneM2M] OneM2M, "oneM2M Service Layer Standards for M2M and IoT", 2017, <<http://www.onem2m.org/>>.
- [Overlay_ICN] Shailendra, S., et al., "A novel overlay architecture for Information Centric Networking", 2015 21st National Conference on Communications, NCC 2015, DOI 10.1109/NCC.2015.7084921, April 2016, <https://www.researchgate.net/publication/282779666_A_novel_overlay_architecture_for_Information_Centric_Networking> .
- [POINT] Trossen, D., et al., "IP over ICN - The better IP?", 2015 European Conference on Networks and Communications (EuCNC), DOI 10.1109/EuCNC.2015.7194109, June 2015, <<https://doi.org/10.1109/EuCNC.2015.7194109>>.
- [Ravindran] Ravindran, R., et al., "5G-ICN : Delivering ICN Services over 5G using Network Slicing", IEEE Communications Magazine, Volume 55, Issue 5, DOI 10.1109/MCOM.2017.1600938, October 2016, <<https://arxiv.org/abs/1610.01182>>.
- [Reed] Reed, M., et al., "Stateless multicast switching in software defined networks", 2016 IEEE International Conference on Communications (ICC),

DOI 10.1109/ICC.2016.7511036, May 2016,
<<https://doi.org/10.1109/ICC.2016.7511036>>.

- [RFC6920] Farrell, S., Kutscher, D., Dannewitz, C., Ohlman, B., Keranen, A., and P. Hallam-Baker, "Naming Things with Hashes", RFC 6920, DOI 10.17487/RFC6920, April 2013, <<https://www.rfc-editor.org/info/rfc6920>>.
- [RFC7252] Shelby, Z., Hartke, K., and C. Bormann, "The Constrained Application Protocol (CoAP)", RFC 7252, DOI 10.17487/RFC7252, June 2014, <<https://www.rfc-editor.org/info/rfc7252>>.
- [RFC7426] Haleplidis, E., Ed., Pentikousis, K., Ed., Denazis, S., Hadi Salim, J., Meyer, D., and O. Koufopavlou, "Software-Defined Networking (SDN): Layers and Architecture Terminology", RFC 7426, DOI 10.17487/RFC7426, January 2015, <<https://www.rfc-editor.org/info/rfc7426>>.
- [RFC7665] Halpern, J., Ed. and C. Pignataro, Ed., "Service Function Chaining (SFC) Architecture", RFC 7665, DOI 10.17487/RFC7665, October 2015, <<https://www.rfc-editor.org/info/rfc7665>>.
- [RFC7927] Kutscher, D., Ed., Eum, S., Pentikousis, K., Psaras, I., Corujo, D., Saucez, D., Schmidt, T., and M. Waehlich, "Information-Centric Networking (ICN) Research Challenges", RFC 7927, DOI 10.17487/RFC7927, July 2016, <<https://www.rfc-editor.org/info/rfc7927>>.
- [RFC7945] Pentikousis, K., Ed., Ohlman, B., Davies, E., Spirou, S., and G. Boggia, "Information-Centric Networking: Evaluation and Security Considerations", RFC 7945, DOI 10.17487/RFC7945, September 2016, <<https://www.rfc-editor.org/info/rfc7945>>.
- [RFC8075] Castellani, A., Loreto, S., Rahman, A., Fossati, T., and E. Dijk, "Guidelines for Mapping Implementations: HTTP to the Constrained Application Protocol (CoAP)", RFC 8075, DOI 10.17487/RFC8075, February 2017, <<https://www.rfc-editor.org/info/rfc8075>>.
- [RFC8568] Bernardos, CJ., Rahman, A., Zuniga, JC., Contreras, LM., Aranda, P., and P. Lynch, "Network Virtualization Research Challenges", RFC 8568, DOI 10.17487/RFC8568, April 2019, <<https://www.rfc-editor.org/info/rfc8568>>.
- [RFC8569] Mosko, M., Solis, I., and C. Wood, "Content-Centric Networking (CCNx) Semantics", RFC 8569, DOI 10.17487/RFC8569, July 2019, <<https://www.rfc-editor.org/info/rfc8569>>.
- [RFC8609] Mosko, M., Solis, I., and C. Wood, "Content-Centric Networking (CCNx) Messages in TLV Format", RFC 8609, DOI 10.17487/RFC8609, July 2019, <<https://www.rfc-editor.org/info/rfc8609>>.
- [RFC8613] Selander, G., Mattsson, J., Palombini, F., and L. Seitz, "Object Security for Constrained RESTful Environments (OSCORE)", RFC 8613, DOI 10.17487/RFC8613, July 2019, <<https://www.rfc-editor.org/info/rfc8613>>.
- [SAIL] SAIL, "Scalable and Adaptive Internet Solutions (SAIL)", <<http://www.sail-project.eu/>>.
- [SAIL_Content_Delivery] FP7, "NetInf Content Delivery and Operations", Objective FP7-ICT-2009-5-257448/D-3.2, January 2013, <https://sail-project.eu/wp-content/uploads/2012/06/SAIL_DB2_v1_0_final-Public.pdf>.

- [SAIL_Prototyping]
FP7, "Prototyping and Evaluation", Objective FP7-ICT-2009-5-257448/D.B.4, March 2013, <http://www.sail-project.eu/wp-content/uploads/2013/05/SAIL_DB4_v1.1_Final_Public.pdf>.
- [Tateson] Tateson, J., et al., "Final Evaluation Report on Deployment Incentives and Business Models", PSIRP, Version 1.0, May 2010, <http://www.psirp.org/files/Deliverables/FP7-INFISO-ICT-216173-PSIRP-D4.6_FinalReportOnDeplIncBusinessModels.pdf>.
- [Techno_Economic]
Trossen, D. and A. Kostopoulos, "Techno-Economics Aspects of Information-Centric Networking", Volume 2, Journal for Information Policy , DOI 10.5325/jinfopoli.2.2012.0026, June 2012, <<https://doi.org/10.5325/jinfopoli.2.2012.0026>>.
- [UMOBILE-2]
Sarros, C., et al., "Connecting the Edges: A Universal, Mobile-Centric, and Opportunistic Communications Architecture", IEEE Communications Magazine, Volume 56, Issue 2, DOI 10.1109/MCOM.2018.1700325, February 2018, <<https://doi.org/10.1109/MCOM.2018.1700325>>.
- [UMOBILE-3]
Tavares, M., Aponte, O., and P. Mendes, "Named-data Emergency Network Services", MobiSys '18: Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services, DOI 10.1145/3210240.3210809, June 2018, <<https://doi.org/10.1145/3210240.3210809>>.
- [UMOBILE-4]
Amaral, L., et al., "Oi! - Opportunistic Data Transmission Based on Wi-Fi Direct", 2016 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPs), DOI 10.1109/INFCOMW.2016.7562142, April 2016, <<https://doi.org/10.1109/INFCOMW.2016.7562142>>.
- [UMOBILE-5]
Dynerowicz, S. and P. Mendes, "Demo: named-data networking in opportunistic network", ICN '17: Proceedings of the 4th ACM Conference on Information-Centric Networking, DOI 10.1145/3125719.3132107, September 2017, <<https://doi.org/10.1145/3125719.3132107>>.
- [UMOBILE-6]
Mendes, P., et al., "Information-centric routing for opportunistic wireless networks", ICN '18: Proceedings of the 5th ACM Conference on Information-Centric Networking, DOI 10.1145/3267955.3269011, September 2018, <<https://doi.org/10.1145/3267955.3269011>>.
- [UMOBILE-7]
Sofia, R., "D4.5 Report on Data Collection and Inference Models", Deliverable, September 2017.
- [UMOBILE-8]
Sarros, C., et al., "ICN-based edge service deployment in challenged networks", ICN '17: Proceedings of the 4th ACM Conference on Information-Centric Networking, DOI 10.1145/3125719.3132096, September 2017, <<https://doi.org/10.1145/3125719.3132096>>.
- [UMOBILE-9]
Lertsinsruttavee, A., et al., "Information-Centric Multi-Access Edge Computing Platform for Community Mesh Networks", COMPASS '18: Proceedings of the 1st ACM SIGCAS Conference on Computing and Sustainable Societies,

DOI 10.1145/3209811.3209867, June 2018,
<<https://doi.org/10.1145/3209811.3209867>>.

[UMOBILE-overview]

UMOBILE, "Universal, mobile-centric and opportunistic communications architecture",
<<http://www.umobile-project.eu/>>.

[VSER]

Ravindran, R., et al., "Towards software defined ICN based edge-cloud services", 2013 IEEE 2nd International Conference on Cloud Networking (CloudNet), DOI 10.1109/CloudNet.2013.6710583, <<https://doi.org/10.1109/CloudNet.2013.6710583>>.

[VSER-Mob]

Azgin, A., et al., "Seamless Producer Mobility as a Service in Information-centric Networks", ACM-ICN '16: Proceedings of the 3rd ACM Conference on Information-Centric Networking, DOI 10.1145/2984356.2988521, September 2016, <<https://doi.org/10.1145/2984356.2988521>>.

[White]

White, G. and G. Rutz, "Content Delivery with Content-Centric Networking", February 2016, <<http://www.cablelabs.com/wp-content/uploads/2016/02/Content-Delivery-with-Content-Centric-Networking-Feb-2016.pdf>>.

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