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        Deployment Considerations for Information-Centric Networking (ICN)
               draft-irtf-icnrg-deployment-guidelines-07

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).

Status of This Memo

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1. Introduction

   The ICNRG 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 which
   avoid forklift upgrades, and defining practical ICN interworking
   configurations with the existing Internet paradigm, are key topic
   areas that require further investigation [ICNRGCharter]. 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
   [I-D.paik-icn-deployment-considerations], 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
[I-D.irtf-icnrg-terminology]. In addition, this document defines the
following terminology:

Deployment - In the context of this document, deployment refers to
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.,
WiFi, Mobile radio network), service edge networks (e.g., for edge
computing), transport networks, CDNs, core networks (e.g., Mobile
core network), and back-end processing networks (e.g., Data
Centres). However, throughout the document we typically limit the
discussion 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 [I-D.irtf-icnrg-terminology] for further
information.

Network Functions Virtualization (NFV): A networking approach
where network functions (e.g., firewalls, 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
[I-D.irtf-nfvrg-gaps-network-virtualization] for further
information.

Software-Defined Networking (SDN) - A networking approach where
the control and data plane for switches are separated, allowing
for realizing capabilities such as traffic isolation and
programmable forwarding actions. See [RFC7426] for further
information.

[3](#). **Acronyms List**

    API - Application Programming Interface

    BIER - Bit Indexed Explicit Replication

    BoF - Birds of a Feather (session)

    CCN - Content Centric Networking

    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 Telecommunication Standards Institute

    EU - European Union

    FP7 - 7th Framework Programme for Research and Technological
    Development

    HLS - HTTP Live Streaming

    HTTP - Hyper Text Transfer Protocol

    HTTPS- Hyper Text 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

ISIS - 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 - Mobile 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 - National Institute of Information and Communications
Technology of Japan

NR - New Radio (access network for 5G)

OAM - Operations 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
   various 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 as well as ancillary
   services such as existing applications which are typically tied
   directly to the TCP/IP protocol 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], CCN routers [Jacobson] or 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

   Similarly 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 such as 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 [I-D.kutscher-icnrg-netinf-proto].
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.

Regardless of the flavor, however, 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, ISIS) 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 which 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 [I-D.irtf-icnrg-icniot].
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 use case scenario, the [VSER] platform shows the realization of a multi-party audio/video conferencing service over such a edge cloud deployment of ICN routers realized over commodity hardware platforms. This platform has also been extended to offer seamless mobility and mobility as a service [VSER-Mob] features.

4.3.2. Core Network

In this sub-option, 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, such as realized in access points or customer premise equipment, which in turn provides a standard IP interface to existing user devices. The NAPs thus provides the apparent perception of an IP-based core network towards 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 enables 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 network enabling dynamic slicing the spectrum resources among various services hence naturally extending itself to end points and also cloud resources across multiple domains, to offer end-to-end guarantees. These slices once instantiated could include a mix of connectivity services like LTE-as-a-service or OTT services like VoD or other IoT services through composition of a group of

virtual and/or physical network functions at control, user and service plane level. 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), Mobile core network, or 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 [I-D.ravi-icnrg-5gc-icn]. The draft elaborates on two possible approaches to enable ICN. First, as an edge service using the local data network (LDN) feature in 5G using UPF classification functions to fast handover to the ICN forwarder; the other is as a native deployment using the non-IP PDU support that would allow new network layer PDU to be handed over to ICN UPFs collocated with the 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 plan enablement, control plane extensions are also proposed leveraging 5GC's interface to other application functions (AF) 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 "chained service functions" [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 an 5G-ICN instance [Ravindran].

At the level of the specific technologies involved, such as ONAP [ONAP] that 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 with SDN as a data plane forwarding function, 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:

o Application providers

o ISPs and service providers, both as core as well as access network providers, and also ICN network providers

o CDN providers (due to the strong relation of the ICN proposition to content delivery)

o End device manufacturers and users

Our focus is on technological aspects of such migration. Economic or regulatory aspects, such as 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), as well as 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, [I-D.irtf-icnrg-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 signalling 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, either 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 increase utilization of available bandwidth as well as reducing the load on origin servers. Similar to the previous sub-section, the underlay deployment configuration presented in Section 4.3 aim at providing a migration path for existing CDNs. This is also highlighted in a BIER use case document [I-D.ietf-bier-multicast-http-response], specifically with potential benefits in terms of utilizing multicast in the delivery of content but also reducing load on origin as well as delegation server. 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. Such IoT deployments have for many years 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 [RFC7252] based 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. With the proliferation of network softwarization (using technologies like service orchestration frameworks leveraging NFV and SDN concepts) access networks and other network segments, the ICN-as-a-Slice deployment configuration in Section 4.4 provides a suitable migration path for integration non-IP-based edge networks into the overall system through 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 AR/VR-based deployments for, 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, and we therefore 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 test bed as an L2 VPN-based overlay
between several European, US as well as 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 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. Reference [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 video-conferencing,
geo-locating, 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 CCN approaches
are within the scope of the project.

ICN2020 has released a set of interim public technical reports
[ICN2020]. The report [ICN2020-Experiments] contains a detailed
description of the progress made in both local testbeds as well as
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,
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] that supports intermittent wireless
networking. UMOBILE also implements a new data-centric wireless
routing protocol, DABBER [UMOBILE-6] [I-D.mendes-icnrg-dabber], which
was designed based on data reachability metrics that take into
consideration availability of adjacent wireless nodes and different
data sources. 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 trails. 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 trail was the ICN deployment over the "Guifi.net" community network in the Barcelona region. This trial focused on the evaluation of 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 as well as 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+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 as well as service endpoint surrogate benefits in HTTP-based scenarios, such as for HTTP-level streaming video delivery, have been demonstrated in the deployed POINT test bed 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 afore-mentioned 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 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 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 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 playout of the video originating from the local NAP, collocated with the WiFi 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 "island of ICN" based CDN is then used to service standard HTTP/IP-based content retrieval request 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 had not yet been tested experimentally but that implementations were 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 multi-story 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 nation-wide VPN-based
L2 underlay. The testbed uses the CCN approach and is based on the
[CICN] open source software. There are approximately 15 nodes spread
across the USA which 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 Securisation 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 a 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 Web sites. The users only need to set
the gateway as the Web proxy. The control-plane relies on a central
manager which uses machine learning based detection methods [Mai-1]
from the date gathered by distributed probes and applies orchestrated
counter-measures 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., CCN, NDN, 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., video-conferencing and IPTV). Another
limitation of the trials is that all of them involve less than 1k
users.

The ICN-as-a-Slice configuration has just started being trialled by
Huawei and China Unicom to demonstrate ICN features of security,
mobility and bandwidth efficiency over a wired infrastructure using
video conferencing 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 trialled 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

The 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 that may be relevant for
further standardization effort in 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
[I-D.irtf-icnrg-ccnxmessages] and [I-D.irtf-icnrg-ccnxsemantics].
Naming dynamically generated data requires different approaches
(e.g., hash digest based names would normally not work), and there is
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 broadcast 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 flavours.

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 light-weight 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 [RFC8613]-like approach, 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, ISIS) and ICN routing approaches(e.g., NFD, CCN 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 utilizing 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 [I-D.moiseenko-icnrg-flowclass] which proposes a flow classification based approach to enable functions such ICN rate control and cache control. Also [I-D.anilj-icnrg-icn-qos] proposes how to use DiffServ 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 modelling 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
CCNinfo [I-D.irtf-icnrg-ccninfo] [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  | Multicast enhancements for ICN                     |
| distribution |                                                    |
|              |                                                    |
| 5-In-network | ICN Cache placement and sharing                    |
| caching      |                                                    |
|              |                                                    |
| 6-NFV/SDN    | Integration of ICN with NFV/SDN and including      |
| support      | possible impacts to SFC                            |
|              |                                                    |
| 7-ICN        | Mapping of HTTP and other protocols onto ICN       |
| mapping      | message exchanges (and vice-versa) while           |
|              | preserving ICN message security                    |
|              |                                                    |
| 8-QoS        | Support of ICN QoS via mechanisms such as DiffServ |
| support      | and flow classification                            |
|              |                                                    |
| 9-OAM        | YANG models, NETCONF/RESTCONF protocols,           |
| support      | and network performance measurements               |
|              |                                                    |
+--------------+----------------------------------------------------+
```

Table 1: 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 (e.g., can it support all required user applications).
   ICN-as-a-Slice is an attractive deployment option for up coming 5G
   systems (i.e., for 5G radio and core networks) which 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 (e.g., 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., CCN, NDN, 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 requests 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 which 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) becomes the norm, that 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 co-existence 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 similiar 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 evaluation of potential counter-measures based on MANO
   orchestrated actions on the virtualized infrastructure [Mai-1] .

[11](#). Acknowledgments

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[12](#). Informative References

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

[Baccelli]
          Baccelli, E. and et al., "Information Centric Networking
          in the IoT: Experiments with NDN in the Wild", ACM
          20164, Paris, France, 2014,
          <http://conferences2.sigcomm.org/acm-icn/2014/papers/
          p77.pdf>.

[C_FLOW]   Suh, J. and et al., "C_FLOW: Content-Oriented Networking
          over OpenFlow", Open Networking Summit, April, 2012,
          <http://opennetsummit.org/archives/apr12/site/pdf/
          snu.pdf>.

[CCNx_UDP]
          PARC, "CCNx Over UDP", 2015,
          <https://www.ietf.org/proceedings/interim-2015-icnrg-
          04/slides/slides-interim-2015-icnrg-4-5.pdf>.

[Chakraborti]
          Chakraborti, A. and et al., "Design and Evaluation of a
          Multi-source Multi-destination Real-time Application on
          Content Centric Network", IEEE, HoT ICN, 2018 , 2018.

[CICN]   CICN, "Community Information-Centric Networking (CICN)",
          2017, <https://wiki.fd.io/view/Cicn>.

[CONET]   Veltri, L. and et al., "CONET Project: Supporting
            Information-Centric Functionality in Software Defined
            Networks", Workshop on Software Defined Networks, , 2012,
            <http://netgroup.uniroma2.it/Stefano_Salsano/papers/
            salsano-icc12-wshop-sdn.pdf>.

[Contrace]
            Asaeda, H. and et al., "Contrace: A Tool for Measuring and
            Tracing Content-Centric Networks", IEEE Communications
            Magazine, Vol.53, No.3 , 2015.

[CUTEi]   Asaeda, H. and N. Choi, "Container-Based Unified Testbed
            for Information Centric Networking", IEEE Network, Vol.28,
            No.6 , 2014.

[DASH]   DASH, "DASH Industry Forum", 2017, <http://dashif.org/>.

[Doctor]   Doctor, "Deployment and Securisation of new
            Functionalities in Virtualized Networking Environments
            (Doctor)", 2017,
            <http://www.doctor-project.org/index.htm>.

[fiveG-23501]
            3gpp-23.501, "Technical Specification Group Services and
            System Aspects; System Architecture for the 5G System
            (Rel.15)", 3GPP , 2017.

[fiveG-23502]
            3gpp-23.502, "Technical Specification Group Services and
            System Aspects; Procedures for the 5G System (Rel.15)",
            3GPP , 2017.

[GEANT]   GEANT, "GEANT Overview", 2016, <https://www.geant.org/>.

[H-ICN_1]   Cisco, "Hybrid ICN: Cisco Announces Important Steps toward
            Adoption of Information-Centric Networking", 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", 2017,
            <https://www.cisco.com/c/dam/en/us/solutions/collateral/
            service-provider/ultra-services-platform/
            mwc17-hicn-video-wp.pdf>.

[H-ICN_3] Muscariello, L. and et al., "Hybrid Information-Centric
           Networking: ICN inside the Internet Protocol", 2018,
           <https://datatracker.ietf.org/meeting/interim-2018-icnrg-
           01/materials/slides-interim-2018-icnrg-01-sessa-hybrid-
           icn-hicn-luca-muscariello>.

[H-ICN_4] Sardara, M. and et al., "(h)ICN Socket Library for HTTP:
           Leveraging (h)ICN socket library for carrying HTTP
           messages", 2018, <https://datatracker.ietf.org/meeting/
           interim-2018-icnrg-01/materials/slides-interim-2018-icnrg-
           01-sessa-hicn-socket-library-for-http-luca-muscariello>.

[I-D.anilj-icnrg-icn-qos]
           Jangam, A., suthar, P., and M. Stolic, "Supporting QoS
           aware Data Delivery in Information Centric Networks",
           draft-anilj-icnrg-icn-qos-00 (work in progress), July
           2018.

[I-D.ietf-bier-multicast-http-response]
           Trossen, D., Rahman, A., Wang, C., and T. Eckert,
           "Applicability of BIER Multicast Overlay for Adaptive
           Streaming Services", draft-ietf-bier-multicast-http-
           response-01 (work in progress), June 2019.

[I-D.irtf-icnrg-ccninfo]
           Asaeda, H., Ooka, A., and X. Shao, "CCNinfo: Discovering
           Content and Network Information in Content-Centric
           Networks", draft-irtf-icnrg-ccninfo-02 (work in progress),
           July 2019.

[I-D.irtf-icnrg-ccnxmessages]
           Mosko, M., Solis, I., and C. Wood, "CCNx Messages in TLV
           Format", draft-irtf-icnrg-ccnxmessages-09 (work in
           progress), January 2019.

[I-D.irtf-icnrg-ccnxsemantics]
           Mosko, M., Solis, I., and C. Wood, "CCNx Semantics",
           draft-irtf-icnrg-ccnxsemantics-10 (work in progress),
           January 2019.

[I-D.irtf-icnrg-icn-lte-4g]
           suthar, P., Stolic, M., Jangam, A., Trossen, D., and R.
           Ravindran, "Native Deployment of ICN in LTE, 4G Mobile
           Networks", draft-irtf-icnrg-icn-lte-4g-03 (work in
           progress), March 2019.

[I-D.irtf-icnrg-icniot]
          Ravindran, R., Zhang, Y., Grieco, L., Lindgren, A., Burke,
          J., Ahlgren, B., and A. Azgin, "Design Considerations for
          Applying ICN to IoT", draft-irtf-icnrg-icniot-03 (work in
          progress), May 2019.

[I-D.irtf-icnrg-terminology]
          Wissingh, B., Wood, C., Afanasyev, A., Zhang, L., Oran,
          D., and C. Tschudin, "Information-Centric Networking
          (ICN): CCN and NDN Terminology", draft-irtf-icnrg-
          terminology-04 (work in progress), June 2019.

[I-D.irtf-nfvrg-gaps-network-virtualization]
          Bernardos, C., Rahman, A., Zuniga, J., Contreras, L.,
          Aranda, P., and P. Lynch, "Network Virtualization Research
          Challenges", draft-irtf-nfvrg-gaps-network-
          virtualization-10 (work in progress), September 2018.

[I-D.kutscher-icnrg-netinf-proto]
          Kutscher, D., Farrell, S., and E. Davies, "The NetInf
          Protocol", draft-kutscher-icnrg-netinf-proto-01 (work in
          progress), February 2013.

[I-D.mendes-icnrg-dabber]
          Mendes, P., Sofia, R., Tsaoussidis, V., Diamantopoulos,
          S., Sarros, C., Borrego, C., and J. Borrell, "Information-
          centric Routing for Opportunistic Wireless Networks",
          draft-mendes-icnrg-dabber-02 (work in progress), February
          2019.

[I-D.moiseenko-icnrg-flowclass]
          Moiseenko, I. and D. Oran, "Flow Classification in
          Information Centric Networking", draft-moiseenko-icnrg-
          flowclass-04 (work in progress), July 2019.

[I-D.paik-icn-deployment-considerations]
          Paik, E., Yun, W., Kwon, T., and h.
          hgchoi@mmlab.snu.ac.kr, "Deployment Considerations for
          Information-Centric Networking", draft-paik-icn-
          deployment-considerations-00 (work in progress), July
          2013.

[I-D.ravi-icnrg-5gc-icn]
          Ravindran, R., suthar, P., Trossen, D., Wang, C., and G.
          White, "Enabling ICN in 3GPP's 5G NextGen Core
          Architecture", draft-ravi-icnrg-5gc-icn-04 (work in
          progress), May 2019.

   [ICN2020] ICN2020, "ICN2020 Deliverables", 2017,
              <http://www.icn2020.org/dissemination/
              deliverables-public/>.

   [ICN2020-Experiments]
              ICN2020, "Deliverable D4.1: 1st yearly report on Testbed
              and Experiments (WP4)", 2017,
              <http://www.icn2020.org/dissemination/
              deliverables-public/>.

   [ICN2020-overview]
              ICN2020, "ICN2020 Project Overview", 2016,
              <http://www.icn2020.org/>.

   [ICNRGCharter]
              NDN, "Information-Centric Networking Research Group
              Charter", 2013,
              <https://datatracker.ietf.org/doc/charter-irtf-icnrg/>.

   [IEEE_Communications]
              Trossen, D. and G. Parisis, "Designing and Realizing an
              Information-Centric Internet", Information-Centric
              Networking, IEEE Communications Magazine Special Issue,
              2012.

   [Internet_Pricing]
              Trossen, D. and G. Biczok, "Not Paying the Truck Driver:
              Differentiated Pricing for the Future Internet", ReArch
              Workshop in conjunction with ACM Context, December, 2010.

   [Jacobson]
              Jacobson, V. and et al., "Networking Named Content",
              Proceedings of ACM Context, , 2009.

   [Jangam]   Jangam, A. and et al., "Porting and Simulation of Named-
              data Link State Routing Protocol into ndnSIM", ACM
              DIVANet'17, Miami Beach, USA, 2017,
              <https://dl.acm.org/citation.cfm?id=3132351>.

   [Mai-1]   Mai, H. and et al., "Implementation of Content Poisoning
              Attack Detection and Reaction in Virtualized NDN
              Networks", 21st Conference on Innovation in Clouds,
              Internet and Networks, ICIN 2018 (demo paper) IEEE, 2018,
              <http://www.mallouli.com/recherche/publications/
              noms2018-1.pdf>.

   [Mai-2]   Mai, H. and et al., "Towards a Security Monitoring Plane
              for Named Data Networking: Application to Content
              Poisoning Attack", Proceedings of the 2018 IEEE/IFIP
              Symposium on Network Operations and Management (NOMS)
              IEEE, 2018.

   [Marchal] Marchal, X. and et al., "Leveraging NFV for the Deployment
              of NDN: Application to HTTP Traffic Transport",
              Proceedings of the 2018 IEEE/IFIP Symposium on Network
              Operations and Management (NOMS), 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", 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 Testbed, "Named Data Networking (NDN) Testbed", 2010,
              <https://named-data.net/ndn-testbed/>.

   [NFD]   NDN, "NFD - Named Data Networking Forwarding Daemon",
              2017, <https://named-data.net/doc/NFD/current/>.

   [NGMN-5G] NGMN, "NGMN 5G White Paper", 2015,
              <https://www.ngmn.org/fileadmin/ngmn/content/images/news/
              ngmn_news/NGMN_5G_White_Paper_V1_0.pdf>.

   [NGMN-Network-Slicing]
              NGMN, "NGMN Description of Network Slicing Concept", 2016,
              <https://www.ngmn.org/fileadmin/
              user_upload/160113_Network_Slicing_v1_0.pdf>.

   [Nguyen-1]
              Nguyen, T. and et al., "Content Poisoning in Named Data
              Networking: Comprehensive Characterization of real
              Deployment", Proceedings of the 15th IEEE/IFIP
              International Symposium on Integrated Network Management,
              2017.

[Nguyen-2]
          Nguyen, T., Cogranne, R., and G. Doyen, "An Optimal
          Statistical Test for Robust Detection against Interest
          Flooding Attacks in CCN", Proceedings of the 14th IEEE/
          IFIP International Symposium on Integrated Network
          Management, 2015.

[Nguyen-3]
          Nguyen, T. and et al., "A Security Monitoring Plane for
          Named Data Networking Deployment", IEEE Communications
          Magazine, Nov 2018.

[ONAP]   ONAP, "Open Network Automation Platform", 2017,
          <https://www.onap.org/>.

[oneM2M] OneM2M, "oneM2M Service Layer Standards for M2M and IoT",
          2017, <http://www.onem2m.org/>.

[Overlay_ICN]
          Shailendra, S. and et al., "A Novel Overlay Architecture
          for F Networking", 2016, <https://www.researchgate.net/pub
          lication/282779666_A_novel_overlay_architecture_for_Inform
          ation_Centric_Networking>.

[POINT]   Trossen, D. and et al., "POINT: IP Over ICN - The Better
          IP?", European Conference on Networks and Communications
          (EuCNC), , 2015.

[Ravindran]
          Ravindran, R. and et al., "5G-ICN : Delivering ICN
          Services over 5G using Network Slicing", IEEE
          Communication Magazine, May, 2016,
          <https://arxiv.org/abs/1610.01182>.

[Reed]   Reed, M. and et al., "Stateless Multicast Switching in
          Software Defined Networks", ICC 2016, Kuala Lumpur,
          Malaysia, 2016.

[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. Waehlisch,
           "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>.

[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)",
           2013, <http://www.sail-project.eu/>.

[SAIL_Content_Delivery]
           FP7, "SAIL Content Delivery and Operations", 2013,
           <https://sail-project.eu/wp-content/uploads/2012/06/
           SAIL_DB2_v1_0_final-Public.pdf>.

[SAIL_Prototyping]
           FP7, "SAIL Prototyping and Evaluation", 2013,
           <http://www.sail-project.eu/wp-content/uploads/2013/05/
           SAIL_DB4_v1.1_Final_Public.pdf>.

[Tateson]   Tateson, J. and et al., "Final Evaluation Report on
            Deployment Incentives and Business Models", 2010,
            <http://www.psirp.org/files/Deliverables/FP7-INFSO-ICT-
            216173-PSIRP-D4.6_FinalReportOnDeplIncBusinessModels.pdf>.

[Techno_Economic]
            Trossen, D. and A. Kostopolous, "Techno-Economics Aspects
            of Information-Centric Networking", Journal for
            Information Policy, Volume 2, 2012.

[UMOBILE-2]
            Sarros, C. and et al., "Connecting the Edges: A Universal,
            Mobile-Centric, and Opportunistic Communications
            Architecture", IEEE Communications Magazine, vol. 56,
            February 2018.

[UMOBILE-3]
            Tavares, M., Aponte, O., and P. Mendes, "Named-data
            Emergency Network Services", Proc. of ACM MOBISYS, Munich,
            Germany, June 2018.

[UMOBILE-4]
            Lopes, L. and et al., "Oi! - Opportunistic Data
            Transmission Based on Wi-Fi Direct", Proc. of IEEE
            INFOCOM, San Francisco, USA, April 2016.

[UMOBILE-5]
            Dynerowicz, S. and P. Mendes, "Named-Data Networking in
            Opportunistic Networks", Proc. of ACM ICN, Berlin,
            Germany, September 2017.

[UMOBILE-6]
            Mendes, P. and et al., "Information-centric Routing for
            Opportunistic Wireless Networks", Proc. of ACM ICN,
            Boston, USA, September 2018.

[UMOBILE-7]
            Sofia, R., "The UMOBILE Contextual Manager Service.
            Technical Report. Technical Report Senception 001, 2018
            (base for UMOBILE deliverable D4.5 - Report on Data
            Collection and Inference Models", 2018.

[UMOBILE-8]
            Sarros, C. and et al., "ICN-based edge service deployment
            in challenged networks", Proceedings of the 4th ACM
            Conference on Information-Centric Networking (ICN '17).
            ACM, New York, NY, USA, 2017 .

[UMOBILE-9]
          Lertsinsrubtavee, A. and et al., "Information-Centric
          Multi-Access Edge Computing Platform for Community Mesh
          Networks", Proceedings of the 1st ACM SIGCAS Conference on
          Computing and Sustainable Societies (COMPASS '18). ACM,
          New York, NY, USA, 2018 .

[UMOBILE-overview]
          UMOBILE, "Universal Mobile-centric and Opportunistic
          Communications Architecture (UMOBILE)", 2018,
          <http://www.umobile-project.eu/>.

[VSER]   Ravindran, R. and et al., "Towards software defined ICN
          based edge-cloud services",
          CloudNetworking(CloudNet), IEEE Internation Conference on,
          IEEE Internation Conference on CloudNetworking(CloudNet),
          2013.

[VSER-Mob]
          Azgin, A. and et al., "Seamless Mobility as a Service in
          Information-centric Networks", ACM ICN Sigcomm, IC5G
          Workshop, 2016.

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

Appendix A. Change Log

[Note to RFC Editor: Please remove this section before publication.]

Changes from draft-irtf-rev-06 to draft-irtf-rev-07:

o Added reference to OSCORE (RFC 8613) which is a way of passing
   end-to-end encrypted content between HTTP and COAP without
   invalidating encryption. Thus it can be a potential model for
   HTTP to ICN, or COAP to ICN, to consider in the future.

o Updated affiliation information for author Ravi Ravindran.

Changes from draft-irtf-rev-05 to draft-irtf-rev-06:

o Various updates to ensure that draft complies with RFC 5743
   (Definition of an Internet Research Task Force (IRTF) Document
   Stream) section 2.1.

Changes from draft-irtf-rev-04 to draft-irtf-rev-05:

o Addressed detailed review comments from Marie-Jose Montpetit.

Changes from draft-irtf-rev-03 to draft-irtf-rev-04:

o Added text from Paulo Mendes and Adisorn Lertsinsrubtavee on
   UMOBILE Trial Experiences.

o Incorporated off-line editorial comments from Hitoshi Asaeda and
   Anil Jangam.

Changes from draft-irtf-rev-02 to draft-irtf-rev-03:

o Editorial update of description and references of Doctor testbed
   as per comments from Guillaume Doyen.

o Ran IETF spell checker tool and corrected various spelling errors.

Changes from draft-irtf-rev-01 to draft-irtf-rev-02:

o Updated description of Doctor testbed as per comments from
   Guillaume Doyen. Also referenced Doctor testbed from the Security
   Considerations section.

o Added "Composite-ICN" configuration to cover the Hybrid ICN and
   similar configurations which do not clearly fit in one of the
   other basic configurations.

o Updated description of the ICN-as-a-Slice configuration to clarify
   that it may also apply to non-5G systems.

Changes from draft-irtf-rev-00 to draft-irtf-rev-01:

o Added text from Michael Kowal describing NREN ICN Testbed.

o Added text from Guillaume Doyen describing Doctor Project.

o Updated text on Hybrid ICN based on input from Luca Muscariello.

Changes from draft-rahman-rev-05 to draft-irtf-rev-00:

o Changed draft status from individual draft-rahman-icnrg-deployment-guidelines-05 to RG adopted draft-irtf-icnrg-deployment-guidelines-00.

Changes from rev-04 to rev-05:

o Added this Change Log in Appendix A.

o Removed references to Hybrid ICN from section 3.2 (ICN-as-an-
   Overlay definition). Instead, consolidated all Hybrid ICN info in
   the Deployment Trial Experiences under a new subsection 5.3 (Other
   Configurations).

o Updated ICN2020 description in Section 5.1.4 with text received
   from Mayutan Arumaithurai and Hitoshi Asaeda.

o Clarified in ICN-as-a-Slice description (section 3.4) that it may
   be deployed on either the Edge (RAN) or Core Network, or the ICN-
   as-a-Slice may be deployed end-to-end through the entire Mobile
   network.

o Added several new references in various sections.

o Various minor editorial updates.

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