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Architectural Considerations of Information-Centric Networking (ICN) Using a Name Resolution Service

Abstract

This document describes architectural considerations and implications related to the use of a Name Resolution Service (NRS) in Information-Centric Networking (ICN). It explains how the ICN architecture can change when an NRS is utilized and how its use influences the ICN routing system. This document is a product of the Information-Centric Networking Research Group (ICNRG).

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1. Introduction

Information-Centric Networking (ICN) is an approach to evolving the Internet infrastructure to provide direct access to Named Data Objects (NDOs) by names. In two common ICN architectures, Named Data Networking (NDN) [NDN] and Content-Centric Networking (CCNx) [CCNx], the name of an NDO is used directly to route a request to retrieve the data object. Such direct name-based routing has inherent challenges in enabling a globally scalable routing system, accommodating producer mobility, and supporting off-path caching. These specific issues are discussed in detail in Section 3. In order to address these challenges, a Name Resolution Service (NRS) has been utilized in the literature as well as the proposals of several ICN projects [Afanasyev] [Zhang2] [Ravindran] [SAIL] [MF] [Bayhan].

This document describes the potential changes in the ICN architecture caused by the introduction of an NRS and the corresponding implication to the ICN routing system. It also describes ICN architectural considerations for the integration of an NRS. The scope of this document includes considerations from the perspective of an ICN architecture and routing system when using an NRS in ICN. A description of the NRS itself is provided in the companion NRS design considerations document [RFC9138], which provides the NRS approaches, functions, and design considerations.

This document represents the consensus of the Information-Centric Networking Research Group (ICNRG). It has been reviewed extensively by the Research Group (RG) members who are actively involved in the research and development of the technology covered by this document. It is not an IETF product and is not a standard.

2. Terminology

Name Resolution Service (NRS): An NRS in ICN is defined as a service that provides the function of translating a content name or a data object name into some other information such as a routable prefix, a locator, an off-path-cache pointer, or an alias name that is more amenable than the input name to forwarding the object request toward the target destination storing the NDO [RFC9138]. An NRS is most likely implemented through the use of a distributed mapping database system. The Domain Name System (DNS) may be used as an NRS. However, in this case, the requirements of frequent updates of NRS records due to the creations of a lot of new NDOs

and changes in their locations in the network need to be considered.

NRS server: An NRS comprises the distributed NRS servers storing the mapping records in their databases. NRS servers store and maintain the mapping records that keep the mappings of content or object name to some other information that is used for forwarding the content request or the content itself.

NRS resolver: The client-side function of an NRS is called an NRS resolver. The NRS resolver is responsible for initiating name resolution request queries that ultimately lead to a name resolution of the target data objects. NRS resolvers can be located in the consumer (or client) nodes and/or ICN routers. An NRS resolver may also cache the mapping records obtained through the name resolution for later usage.

Name registration: In order to populate the NRS, the content names and their mapping records must be registered in the NRS system by a publisher who has access rights to at least one authoritative NRS server or by a producer who generates named data objects. The records contain the mapping of an object name to some information such as other alias names, routable prefixes, and locators, which are used for forwarding the content request. Thus, a publisher or producer of content creates an NRS registration request and sends it to an NRS server. On registration, the NRS server stores (or updates) the name mapping record in the database and sends an acknowledgement back to the producer or publisher that made the registration request.

Name resolution: Name resolution is the main function of the NRS system. It is performed by an NRS resolver, which can be deployed on a consumer node or an ICN router. Resolvers are responsible for either returning a cached mapping record (whose lifetime has not expired) or alternatively sending a name resolution request toward an NRS server. The NRS server searches for the content name in its mapping record database and, if found, retrieves the mapping record and returns it in a name resolution response message to the NRS resolver.

NRS node: NRS servers are also referred to as NRS nodes that maintain the name records. The terms are used interchangeably.

NRS client: A node that uses the NRS is called an NRS client. Any node that initiates a name registration, resolution, or update procedure is an NRS client; that is, NRS resolvers, ICN client nodes, ICN routers, or producers can be NRS clients.

3. Background

A pure name-based routing approach in ICN has inherent challenges in enabling a globally scalable routing system, accommodating producer mobility, and supporting off-path caching. In order to address these challenges, an NRS has been utilized in proposals and literature of several ICN projects as follows:

Routing scalability: In ICN, application names identifying content are intended to be used directly for packet delivery, so ICN routers run a name-based routing protocol to build name-based routing and forwarding tables. Similar to the scalability challenge of IP routing, if non-aggregatable name prefixes are injected into the Default Route Free Zone (DFZ) of ICN routers, they would be driving the uncontrolled growth of the DFZ routing table size. Thus, providing the level of indirection enabled by an NRS in ICN can be an approach to keeping the routing table size under control. The NRS system resolves name prefixes that do not exist in the DFZ forwarding table into globally routable prefixes such as the one proposed in NDN [Afanasyev]. Another approach dealing with routing scalability is the Multi-level Distributed Hash Table (MDHT) used in NetInf [Dannewitz]. It provides name-based anycast routing that can support a non-hierarchical namespace and can be adopted on a global scale [Dannewitz2].

Producer mobility: In ICN, if a producer moves into a different name domain that uses a different name prefix, the request for a content produced by the moving producer with the origin content name must be forwarded to the moving producer's new location. Especially in a hierarchical naming scheme, producer mobility support is much harder than in a flat naming scheme since the routing tables in a broader area need to be updated to track the producer movement. Therefore, various ICN architectures such as NetInf [Dannewitz] and MobilityFirst [MF] have adopted NRS systems to tackle the issues of producers whose location changes.

Off-path caching: In-network caching is a common feature of an ICN architecture. Caching approaches can be categorized into on-path caching and off-path caching, according to the location of caches in relation to the forwarding path from the original content store to a consumer. Off-path caching, sometimes also referred to as content replication or content storing, aims to replicate a Named Data Object in various locations within a network in order to increase the availability of content, reduce access latency, or both. These caching locations may not be lying along the content forwarding path. Thus, finding off-path cached content requires more complex forwarding procedures if a pure name-based routing is employed. In order to support access to off-path caches, the locations of replicas are usually advertised into a name-based routing system or into an NRS as described in [Bayhan].

This document discusses architectural considerations and implications of ICN when an NRS is utilized to solve such challenges facing a name-based routing in ICN.

4. Implications of an NRS in ICN

An NRS is not a mandatory part of an ICN architecture, as the majority of ICN architectures uses name-based routing that avoids the need for a name resolution procedure. Therefore, the utilization of an NRS in an ICN architecture changes some architectural aspects at least with respect to forwarding procedures, latency, and security, as discussed below:

Forwarding procedure: When an NRS is included in an ICN architecture, the name resolution procedure has to be included in the ICN overall routing and forwarding architectural procedures. To integrate an NRS into an ICN architecture, there are certain things that have to be decided and specified such as where, when, and how the name resolution task is performed.

Latency: When an NRS is included in an ICN architecture, additional latency introduced by the name resolution process is incurred by the routing and forwarding system. Although the latency due to the name resolution is added, the total latency of individual requests being served could be lower if the nearest copies or off-path caches can be located by the NRS lookup procedure. Additionally, there might be a favorable trade-off between the name resolution latency and inter-domain traffic reduction by finding the nearest off-path cached copy of the content. Finding the nearest cache holding the content might significantly reduce the content discovery as well as delivery latency.

Security: When any new component such as an NRS is introduced in the ICN architecture, the attack surface may increase. Protection of the NRS system itself against attacks such as Distributed Denial of Service (DDoS) and spoofing or alteration of name mapping records and related signaling messages may be challenging.

5. ICN Architectural Considerations for NRS

This section discusses the various items that can be considered from the perspective of ICN architecture when employing an NRS system. These items are related to the registration, resolution, and update of name mapping records, protocols and messages, and integration with the routing system.

5.1. Name Mapping Records Registration, Resolution, and Update

When an NRS is integrated in ICN architecture, the functions related to the registration, resolution, and update of name mapping records have to be considered. The NRS nodes maintain the name mapping records and may exist as an overlay network over the ICN routers, that is, they communicate to each other through ICN routers. Figure 1 shows the NRS nodes and NRS clients connected through an underlying network. The NRS nodes should be deployed in such a manner that an NRS node is always available at a short distance from an NRS client so that communication latency for the name registration and resolution requested by the NRS client remains very low. The name registration, name resolution, and name record update procedures are briefly discussed below.

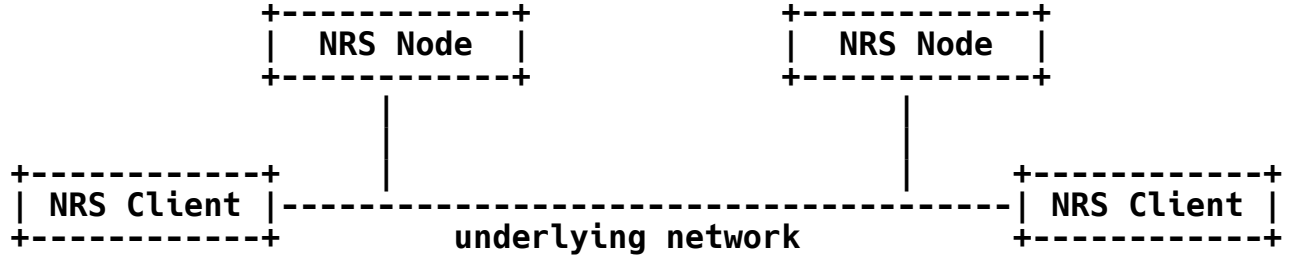

Figure 1: NRS Nodes and NRS Clients Connected through an Underlying Network

Name registration: Name registration is performed by the producer (as an NRS client) when it creates a new content. When a producer creates content and assigns a name from its name prefix space to the content, the producer performs the name registration in an NRS node. Name registration may be performed by an ICN router when the ICN architecture supports off-path caching or cooperative caching since involving an NRS may be a good idea for off-path caching. The ICN routers with forwarder caches do not require name registration for their cached content because they lie on the path toward an upstream content store or producer. They will be hit when a future request is forwarded to the content producer by an ICN router lying downstream toward the ICN client node. However, ICN routers performing off-path caching of content must invoke the name registration procedure so that other ICN routers can depend on name resolutions to know about the off-path cache locations. If a content gets cached in many off-path ICN routers, all of them may register the same content names in the same NRS node, resulting in multiple registration actions. In this case, the NRS node adds the new location of the content to the name record together with the previous locations. In this way, each of the name records stored in the NRS node may contain multiple locations of the content. Assigning validity time or a lifetime of each mapping record may be considered especially for the off-path caching content and managing mobility.

Name resolution: Name resolution is performed by an NRS client to obtain the name record from an NRS node by sending a name resolution request message and getting a response containing the record. In the name-based ICN routing context, the name resolution is needed by any ICN router whose forwarding information base (FIB) does not contain the requested name prefix. Name resolution may also be performed by the consumer (especially in the case where the consumer is multihomed) to forward the content request in a better direction so that it obtains the content from the nearest cache. If the consumer is single homed, it may not bother to perform name resolution, instead depending on either straightforward name-based routing or name resolution by an upstream ICN router. In this case, the consumer creates the content request packet containing the content name and forwards to the nearest ICN router. The ICN router checks its FIB table to see where to forward the content request. If the ICN router fails to identify whether the requested content is reachable, it performs name resolution to obtain the name mapping record and adds this information to its FIB. The ICN router may also perform name resolution even before the arrival of a content request to use the name mapping record to configure its FIB.

Name record update: Name record update is carried out when a content name mapping record changes, e.g., the content is not available in one or more of the previous locations. The name record update includes the substitution and deletion of the name mapping

records. The name record update may take place explicitly by the exchange of name record update messages or implicitly when a timeout occurs and a name record is deemed to be invalid. The implicit update is possible when each record is accompanied by a lifetime value. The lifetime can be renewed only by the authoritative producer or node. The cached mapping records get erased after the lifetime expires unless a lifetime extension indication is obtained from the authoritative producer.

5.2. Protocols and Semantics

In order to develop an NRS system within a local ICN network domain or global ICN network domain, new protocols and semantics must be designed and implemented to manage and resolve names among different namespaces.

One way of implementing an NRS for CCNx is by extending the basic TLV format and semantics [RFC8569] [RFC8609]. For instance, name resolution and response messages can be implemented by defining new type fields in the Interest and Content Object messages [CCNxNRS]. By leveraging the existing CCNx Interest and Content Object packets for name resolution and registration, the NRS system can be deployed with a few ICN protocol changes. However, because of confining the changes to the basic ICN protocol and semantics, the NRS system may not be able to exploit more flexible and scalable designs.

On the other hand, an NRS system can be designed independently with its own protocol and semantics like the NRS system described in [Hong]. For instance, the NRS protocol and messages can be implemented by using a RESTful API, and the NRS can be operated as an application protocol independent of the rest of the ICN protocol.

5.3. Routing System

An NRS reduces the routing complexity of ICN architecture compared to pure name-based routing. It does so by permitting the routing system to update the routing table on demand with the help of name records obtained from NRS. The routing system therefore needs to make name resolution requests and process the information returned, such as a prefix, a locator, an off-path-cache pointer, or an alias name, obtained from the name resolution.

No matter what kind of information is obtained from the name resolution, as long as it is in the form of a name, the content request message in the routing system may be reformatted with the obtained information. In this case, the content name requested originally by a consumer needs to be involved in the reformatted content request to check the integrity of the binding between the name and the requested content. In other words, the information obtained from the name resolution is used to forward the content request, and the original content name requested by a consumer is used to identify the content. Alternatively, the resolved information may be used to build the routing table.

The information obtained from name resolution may not be in the form of a name. For example, it may identify tunnel endpoints by IP

address and instead be used to construct an IP protocol tunnel through which to forward the content request.

6. Conclusion

A Name Resolution Service (NRS) is not a mandatory part in an ICN architecture, as the majority of ICN architectures use name-based routing that does not employ a name resolution procedure. However, such name-based routing in ICN has inherent challenges in enabling a globally scalable routing system, accommodating producer mobility, and supporting off-path caching. In order to address these challenges, an NRS system has been introduced in several ICN projects. Therefore, this document describes how the ICN architecture changes when an NRS is utilized and how this affects the ICN routing system.

The document defines a few terminologies related to an NRS and explains some inherent challenges of pure name-based routing in ICN such as routing scalability, producer mobility, and off-path caching. This document describes how the ICN architecture would change with respect to procedures, latency, and security when an NRS is utilized. According to the ICN architectural changes, this document describes ICN architectural considerations for NRS such as the functions related to the registration, resolution and update of name mapping records, protocols and semantics to implement an NRS system, and the routing system involving the name resolution.

7. IANA Considerations

This document has no IANA actions.

8. Security Considerations

When any new component such as an NRS is introduced in the ICN architecture, the attack surface increases. The related security vulnerability issues are discussed below:

Namespace security: In order to deploy an NRS system in ICN architecture, ICN namespaces, which may be assigned by authoritative entities, must be securely mapped to the content publishers and securely managed by them. According to the ICN research challenges [RFC7927], a new namespace can also provide an integrity verification function to authenticate its publisher. The issues of namespace authentication and the mapping among different namespaces require further investigation.

NRS system security: An NRS requires the deployment of new entities (e.g., NRS servers) to build distributed and scalable NRS systems. Thus, the entities, e.g., an NRS server maintaining a mapping database, could be the focus of attacks by receiving malicious requests from innumerable adversaries comprising of Denial-of-Service or Distributed-Denial-of-Service attacks. In addition, NRS clients in general must trust the NRS nodes in other network domains to some degree, and communication among them must also be protected securely to prevent malicious entities from participating in this communication. The history of name

resolution data requires to be stored and analyzed as in passive DNS to uncover potential security incidents or discover malicious infrastructures.

NRS protocol and message security: In an NRS system, the protocols to generate, transmit, and receive NRS messages related to the name registration, resolution, and record update should be protected by proper security mechanisms. Proper security measures must be provided so that only legitimate nodes can initiate and read NRS messages. These messages must be secured by integrity protection and authentication mechanisms so that unauthorized parties cannot manipulate them when being forwarded through the network. Security measures to encrypt these messages should also be developed to thwart all threats to both security and privacy. Numerous problems similar to the security issues of an IP network and DNS can affect the overall ICN architecture. The DNS QNAME minimization type of approach would be suitable for preserving privacy in the name resolution process. Therefore, security mechanisms such as accessibility, authentication, etc., for the NRS system [RFC9138] should be considered to protect not only the NRS system but also the ICN architecture overall.

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