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# Network Coding for Content-Centric Networking / Named Data Networking: Requirements and Challenges
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Abstract

This document describes the current research outcomes in Network Coding (NWC) for Content-Centric Networking (CCNx) / Named Data Networking (NDN), and clarifies the technical considerations and potential challenges for applying NWC in CCNx/NDN.

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## 1. Introduction

Information-Centric Networking (ICN) in general, and Content-Centric Networking (CCNx) [16] or Named Data Networking (NDN) [18] in particular, have emerged as a novel communication paradigm advocating the retrieval of data based on their names. This paradigm pushes content awareness into the network layer. It is expected to enable consumers to obtain the content they desire in a straightforward and efficient manner from the heterogenous networks they may be connected to. The CCNx/NDN architecture has introduced innovative ideas and has stimulated research in a variety of areas, such as in-network caching, name-based routing, multipath transport, content security. One key benefit of requesting content by name is that it eliminates the requirement of establishing a session between the client and a specific server, and the content can thereby be retrieved from multiple sources.

In parallel, there has been a growing interest in both academia and industry for better understanding the fundamental aspects of Network Coding (NWC) toward enhancing key system-performance metrics such as data throughput, robustness and reduction in the required number of transmissions through connected networks, and point-to-multipoint connections. NWC is a technique that is typically used for encoding packets for recovering lost source packets at the receiver, and for effectively obtaining the desired information in a fully distributed manner. In addition, NWC can be used for security enhancements [2] [3] [4] [5].

From the perspective of the NWC transport mechanism, NWC can be categorized into two major categories: coherent NWC, and non-coherent NWC [35]. In coherent NWC, the source and destination nodes know the exact network topology and the coding operations at intermediate nodes. When multiple consumers are attempting to receive the same content such as live video streaming, coherent NWC could enable optimal throughput sending the content flow over the constructed optimal multicast trees [29]. However, it requires a fully adjustable and specific routing mechanism, and a large computational capacity for central coordination. In the case of non-coherent NWC, that often comprises the use of Random Linear Coding (RLC), it is not necessary to know the network topology nor the intermediate coding operations [30]. As non-coherent NWC works in a completely independent and decentralized manner, this approach is more feasible especially in the large-scale use cases.

NWC combines multiple packets together with parts of the same content, and may do this at the source or at other nodes in the network. Network coded packets are not connected to a specific server, as they may have been combined within the network. As NWC is focused on what information should be encoded in a network packet instead of the specific host at which it has been generated, it is in line with the CCNx/NDN core networking layer. NWC has already been implemented for information/content dissemination [6] [7] [8]. Montpetit, et al., first suggested that NWC techniques be exploited to enhance key system performances in ICN [9]. NWC provides CCNx/NDN with the highly beneficial potential of effectively disseminating information in a completely independent and decentralized manner.

In this document, we consider how NWC can be applied to the CCNx/NDN architecture and describe the technical considerations and potential challenges for making CCNx/NDN-based communications better using the NWC technology. It should be noted that the presentation of specific solutions (e.g., NWC optimization methods) for enhancing CCNx/NDN performance metrics by exploiting NWC is outside the scope of this document.

## 2. Terminology

This section provides the terminology definitions related to NWC and CCNx/NDN used in this document.

### 2.1. Definitions related NWC

The terminologies regarding NWC used in this document are defined as follows. These are aligned with RFCs produced by the FEC Framework (FECFRAME) IETF Working Groups as well as IRTF Coding for Efficient Network Communications Research Group (NWCRG)[21].

The definitions of the general terminologies used are as follows:

- Source Packet: A packet originating from the source that contributes to one or more source symbols. The source symbol is a unit of data originating from the source that is used as input to encoding operations. For instance, an real-time transport protocol (RTP) packet as a whole can constitute a source symbol. In other situations (e.g., to address variable size packets), a single RTP packet may contribute to various source symbols.

- Coded Packet, or Repair Packet: A packet containing one or more coded symbols (also called repair symbol). The coded symbol is a unit of data that is the result of a coding operation, applied either to source symbols or (in case of recoding) source and/or coded symbols. When there is a single coded symbol per coded packet, a coded symbol corresponds to a coded packet.

- Innovative Packet: A source or coded packet that increases the rank of the linear system (also called degrees of freedom) at a receiver.

- Encoding versus Recoding versus Decoding: Encoding is an operation that takes source symbols as input and produces encoding symbols (source or coded symbols) as output. Recoding is an operation that takes encoding symbols as input and produces encoding symbols as output. Decoding is an operation takes encoding symbols as input and produces source symbols as output.

The terminology definitions regarding coding types are as follows:

- Random Linear Coding (RLC): Particular case of linear coding using a set of random coding coefficients. Linear coding linearly combines a set of input source and/or coded symbols using a given set of coefficients and resulting in a coded symbol. Many linear codes exist that differ from the way coding coefficients are drawn from a finite field of a given size.

- Block Coding: Coding technique wherein the input flow(s) must be first segmented into a sequence of blocks; encoding and decoding are performed independently on a per-block basis.

- Sliding Window Coding or Convolutional Coding: General class of coding techniques that rely on a sliding encoding window. Encoding window is a set of source (and coded in the case of recoding) symbols used as input to the coding operations. The set of symbols change over time, as the encoding window slides over the input flow(s). This is an alternative solution to block coding.

- Fixed or Elastic Sliding Window Coding: Coding technique that generates coded symbol(s) on the fly, from the set of source symbols present in the sliding encoding window at that time, usually by using linear coding. The sliding window may be either of fixed size or of variable size over the time (also known as "Elastic Sliding Window"). For instance, the size may depend on acknowledgments sent by the receiver(s) for a particular source symbol or source packet (received, decoded, or decodable).

The terminology definitions regarding low-level coding aspects are as follows:

- Rank of the Linear System or Degrees of Freedom: At a receiver, the number of linearly independent equations of the linear system. It is also known as "Degrees of Freedom". The system may be of "full rank," wherein decoding is possible, or "partial rank", wherein only partial decoding is possible.

- Generation, or Block: With block codes, the set of source symbols of the input flow(s) that are logically grouped into a block, before doing encoding.

- Generation Size, or Block Size: With block codes, the number of source symbols belonging to a block. It is equivalent to the number of source packets when there is a single source symbol per source packet.

- Generation ID, or Block ID: With block codes, the identifier of a block to which source and coded symbols belong. It is also known as "Source Block Number (SBN)".

- Coding Coefficient: With linear coding, this is a coefficient in a certain finite field. This coefficient may be chosen in different ways: for instance, randomly, in a predefined table, or using a predefined algorithm plus a seed.

- Coding Vector: A set of coding coefficients used to generate a certain coded symbol through linear coding.

- Finite Field: Finite fields, used in linear codes, have the desired property of having all elements (except zero) invertible for + and * and all operations over any elements do not result in an overflow or underflow. Examples of finite fields are prime fields {0..p^m-1}, where p is prime. Most used fields use p=2 and are called binary extension fields {0..2^m-1}, where m often equals 1, 4 or 8 for practical reasons.

- Finite Field size: The number of elements in a finite field. For example the binary extension field {0..2^m-1} has size q=2^m.

## 2.2. Definitions related to CCNx/NDN

The terminologies regarding CCNx/NDN used in this document are defined below. They are consistent with the RFCs produced by the Information-Centric Networking (ICNRG) IRTF Working Group[1] [17].

- Interest: A message requesting a content object with a matching name and other optional selectors for selecting from multiple objects having the same name prefix.

- Content Object: A unit of content data delivered through the CCNx/NDN network.

- Consumer: A node requesting a name (i.e., content). It initiates the name-based communication by sending an interest packet.

- Publisher: A node that provides content. It originally creates or owns a content.

- Router: An intermediate node between the consumer and producer that facilitates the name-based communication by forwarding interest and data packets.

- Forwarding Information Base (FIB): A lookup table in a content router containing the name prefix and corresponding destination interface for forwarding the interest packets.

- Pending Interest Table (PIT): A lookup table populated by the interest packets containing the name prefix of the requested data, and the outgoing interface used to forward the received data packets.

- Content Store (CS): A storage space for a router to cache content objects.

## 3. CCNx/NDN Basics

We briefly explain the key concepts of CCNx/NDN. Both protocols are similar in principle, and also different in terms of some implementation choices.

In a CCNx network, there are two types of packets at the network level: interest and data. The consumer requests a content object by sending an interest that carries the name of the data. One difference to note here between CCNx and NDN is that in CCNx [17], the interest is required to a full name, while in NDN [19], it may carry a name prefix (and receive in return any data with a name matching this prefix).

Once a router receives an interest, it performs a series of lookups: first it checks if it has a copy of the requested content object available in the Content Store (CS). If it does, it returns the data, and the transaction is considered to have been successfully completed.

If it does not have a copy of the requested content object in the CS, it performs a lookup of the PIT to check if there is already an outgoing interest for the same content object. If there is no such interest, then it creates an entry in the PIT that lists the name included in the interest, and the interfaces from which it received the interest. This is later used to send the content object back, as interest packets do not carry a source field that identifies the consumer. If there is already a PIT entry for this name, it is updated with the incoming interface of this new interest, and the interest is discarded.

After the PIT lookup, the interest undergoes a FIB lookup for selecting an outgoing interface. The FIB lists name prefixes and their corresponding forwarding interfaces in order to send the interface towards a router that possesses a copy of the requested data.

Once a copy of the data is retrieved, it is sent back to the consumer(s) using the trail of PIT entries; routers remove the PIT state every time that an interest is satisfied, and may store the data in their CS.

Data packets carry some information for validating the data, and in particular, that the data is indeed that which corresponds to the name. This is necessary because authentication of the object is crucial in CCNx/NDN. However, this step is optional at routers in order to speed up the processing.

The key aspect of CCNx/NDN is that the consumer of the content does not establish a session with a specific server. Indeed, the router or publisher that returns the content object is not aware of the network location of the consumer and the consumer is not aware of the network location of the node that provides the content. This, in theory, allows the interests to follow different paths within a network or even to be sent over completely different networks.

## 4. NWC Basics

While the forwarding node simply relays received data packets in conventional IP communication networks, NWC allows the node to combine some data packets that are already received into one or several output packets to be sent. In this section, we simply describe the basic operations of NWC. Herein, we focus on RLC in a block coding manner that is well known as a major coding technique.

For simplicity, let us consider an example case of end-to-end coding wherein a publisher and consumer perform encoding and decoding for a content. This end-to-end coding is regarded as a special case of NWC. The publisher splits the content into several blocks called generations. Encoding and decoding are performed independently on a per-block (per-generation) basis. Let us assume that each generation consists of K original source packets of the same size. When the packets do not have the same size, zero padding is added. In order to generate one coded packet within a certain generation, the publisher linearly combines K of the original source packets, where additions and multiplications are performed using a coding vector consisting of K coding coefficients that are randomly selected in a certain finite field. The publisher may send some or all of the source packets as well as coded packets in the content flow (called systematic coding), where the coded packets (also called repair packets) are typically used for repairing lost source packets.

Coded packets can also be used for performing encoding. If the forwarding nodes know each coding vector and generation identifier of the received coded packets, they may perform an encoding operation (called recoding), which is the most prominent operation in NWC.

At the consumer, decoding is performed by solving a set of linear equations that are represented by the coding vectors of the received coded packets within a certain generation. In order to obtain all the source packets, the consumer requires K linearly independent equations. In other words, the consumer must receive at least K linearly independent data packets (called innovative packets). As receiving a linearly dependent data packet is not useful for decoding, recoding should generate and provide innovative packets. One of major benefits of RLC is that even for a small-sized finite

field (e.g., q=2^8), the probability of generating linearly dependent packets is negligible [29].

## 5. Advantages of NWC and CCNx/NDN

NWC and CCNx/NDN can contribute to effective large-scale content/information dissemination. They both provide similar benefits such as throughput/capacity gain and robustness enhancement. The difference between their approaches is that, the former considers content flow as algebraic information that is to be combined [20], while the latter focuses on the content/information itself at the networking layer. Because these approaches are complementary and their combination would be advantageous, it is natural to combine them.

The name-based communication in CCNx/NDN enables consumers to obtain requested content objects without establishing and maintaining continuous end-to-end communication channels between nodes. This feature facilitates the exploitation of the in-network cache and multipath/multisource retrieval and also supports consumer mobility without the need for updating the location information/identifier during handover [16]. Furthermore, the name-based communication intrinsically supports multicast communication because identical interests are aggregated at the routers.

CCNx/NDN does not provide reliable and robust content dissemination by default. However, NWC can enable the CCNx/NDN transport system to effectively distribute and cache the data associated with multipath data retrieval [9]. Furthermore, NWC can contribute to improving both the caching performance and cache privacy that CCNx/NDN newly introduces at the networking layer [27]. Others also have introduced some use cases of the application of NWC in CCNx/NDN, such as the cases of content dissemination with in-network caching [10] [13] [14], seamless consumer mobility [11] [33], and low-latency low-loss video streaming [15]. In this context, it is well worth considering NWC integration in CCNx/NDN.

## 6. Technical Considerations

This section presents the considerations for CCNx/NDN with NWC in terms of network architecture and protocol. This document focuses on NWC in a block coding manner.

### 6.1. Content Naming

Naming content objects is as important for CCNx/NDN as naming hosts is in the current-day Internet [22]. In this section, two possible naming schemes are presented.

Each coded packet may have a unique name as content objects (original source packets) has in CCNx/NDN, as PIT/CS operations typically require a unique name for identifying the coded packet. As a method of naming a coded packet, the coding vector and the identifier of the generation (also called block) can be used as a part of the content object name. For instance, when the generation ID is g-id, generation size is 4, and coding vector is (1,0,0,0), the name could be /CCNx.com/video-A/g-id/1000. This naming scheme is simple and can support the delivery of coded packets with exactly the same operations in the PIT/CS as those for the content objects.

If a content-naming schema such as the on presented above is used, an interest requesting a coded packet may have the full name including a generation id and coding vector (/CCNx.com/video-A/g-id/1000) or only the name prefix including only a generation id (/CCNx.com/video-A/g-id). In the former case, exact name matching to the PIT is simply performed at data forwarders (as in CCNx). The consumer is enabled to specify and retrieval an innovative packet necessary for the consumer. This could shift the generation of the coding vector from the data forwarder onto the consumer.

In the latter case, partial name matching is required at the data forwarders (as in the case of NDN). As the interest with only the prefix name matches any coded packet with the generation ID, the consumer could immediately obtain an coded packet from a nearby CS (in-network cache) without knowing the coding vectors of the cached coded packets in advance. In the case wherein coded packets in transit are modified by in-network recoding performed at routers, the consumer could also receive the modified coded packets. However, in contrast to the former case, the consumer may fail to obtain sufficient degrees of freedom (see Section 6.2.3). To address this issue, a new TLV type of interest message may be required for specifying further coding information in order to limit the coded packets to be received. For instance, this is enabled by specifying the coding vectors of innovative packets for the consumer (also called decoding matrix) as in [9]. This extension may incur an interest packet of significantly increased size, and it may thus be useful to use compression techniques for coding vectors [24] [25]. Without such coding information provided by the interest, the forwarder would be required to maintain some records regarding the interest packets that were satisfied previously (See Section 6.2.3).

A coded packet may have a name that indicates that it is a coded packet, and move the coding information into a metadata field in the payload (i.e., the name includes the data type, source or coded packet). This would not be beneficial for applications or services that may not need to understand the packet payload. Owing to the possibility that multiple coded packets may have the same name, some

mechanism is required for the consumer to obtain innovative packets. As described in Section 6.3, a mechanism for managing the multiple innovative packets in the CS would also be required. In addition, extra computational overhead would be incurred when the payload is being encrypted.

### 6.2. Transport

The pull-based request--response feature of CCNx/NDN is a fundamental principle of its transport layer; one interest retrieves at most one data packet. It is believed that it is important that this rule not be violated, as it would open denial-of -service (Dos) attacks, and thus, the following basic operation should be considered for applying NWC to CCNx/NDN. Nevertheless, such security considerations should be addressed if this rule were to be violated.

#### 6.2.1. Scope of NWC

It should be discussed whether data forwarder can perform in-network recoding with data packets that are being received in transit, or if only the data that matches an interest can be subject to NWC operations. In the latter case, encoding or recoding is performed to generate the coded packet on an end-to-end coding basis (where one end is the consumer and the other end is any forwarder that is able to respond to the interest). This could occur when each coded packet has a unique name and interest has the full name. On the other hand, if interest has a partial name without any coding vector information or coded packets have a same name, the former case may occur; recoding occurs anywhere in the network where it is possible to modify the received coded packet and forward it. As CCNx/NDN comprises mechanisms for ensuring the integrity of the data during transfer, in-network recoding introduces complexities in the network that would require the consideration of the integrity mechanisms to still work. Similarly, in-network caching of coded packets at routers may be valuable; however, the routers would require some mechanisms to validate the coded packets (see Section 8).

#### 6.2.2. Consumer Operation

To obtain NWC benefits (possibly associated with in-network caching), the consumer is required to issue interests that direct the router (or publisher) to forward innovative packets if available. When issuing an interest specifying a unique name with g-id and the coding vector for a coded packet, the consumer could appropriately receive an innovative packet if it is available at some forwarders. However, the consumer is required to know the naming structure (through a specific name resolution scheme for instance) in order to specify the exact name of the coded packet to be retrieved. In this end-to-end

coding case, if the consumer wants to adjust some coding parameters at the publisher, some specific scheme would be required to be used.

Conversely, the consumer without decoding capability (e.g., specific sensor node) may want to receive only the source packets. As described in Section 6.1, because the coded packet can have a name that is explicitly different from source packets, issuing interests for retrieving source packets is possible. In NDN, if the interest has only the name prefix, as in the case of /NDN.com/file-A, without any selectors, a forwarder may return a matching codec packet.

### 6.2.3. Router Operation

If the router constantly responds to the incoming interests by returning non-innovative packets, the consumer(s) cannot decode and obtain the source packets for all time. This issue could happen when 1) incoming interests for coded packets do not specify some coding parameters such as the coding vectors to be used, and 2) the router does not have a sufficient number of linearly independent source or coded packets (possibly in the CS) to use for recoding. In this case, the router is required to determine whether or not it can generate innovative packets to be forwarded to the interface(s) at which the interests arrived. An approach to deal with this issue is that the router maintains a tally of the interests for a specific name, generation ID and the incoming interface(s), in order to record how many degrees of freedom have already been provided [10]. As such a scheme requires state management (and potentially timers) in routers, scalability and practicality should be considered. In addition, some transport mechanism of in-network loss detection and recovery [15] [33] at router as well as a consumer-driven mechanism could be indispensable for enabling fast loss recovery and enhancing NWC gains. After determining that an innovative packet cannot be provided, according to the FIB, the router relays the received interests to the upstream router(s) or publisher to obtain innovative packets. In this context, to retrieve innovative packet effectively and quickly, an appropriate setting of the FIB and efficient interest forwarding strategies should also be considered.

In another possible case, when receiving interests only for source packets, the router may attempt to decode and obtain all the source packets and store them (if the full cache capacity are available), thus enabling a faster response to the interests. As recoding or decoding results in an extra computational overhead, the router is required to determine how to respond to receiving interests according to the use case (e.g., a delay-sensitive or delay-tolerant application) and the router situation, such as available cache space and computational capability.

### 6.2.4. Publisher Operation

Before performing NWC for specified content in CCNx/NDN, the publisher is responsible for splitting the overall content into small content objects to avoid packet fragmentation that could cause unnecessary packet processing and degraded throughput. The size of the content objects should be within the allowable packet size in order to avoid packet fragmentation in CCNx/NDN network. The publisher performs the encoding operation for a set of the small content objects, and the naming process for the coded packets.

If the producer takes the lead in determining the used coding vectors and generating the coding packets, there exists two possible end-to-end coding cases; 1) consumers obtain the names of the coded packets through a certain mechanism, and send the corresponding interests toward the publisher to obtain the coded packets that have already been generated at the publisher; and 2) the publisher determines the coding vectors after receiving the interests specifying them. In the former case, although the consumers cannot flexibly specify a coding vector for generating the coded packet to obtain, the latency for obtaining the coded packet can be reduced as compared that in the latter case wherein additional NWC operations are required to be performed after receiving the interests. The common benefit in such end-to-end coding cases is that if the publisher adds a signature on the coded packets, data validation becomes possible throughout as in the case of normal CCNx/NDN operations. According to the application requirement for latency, such an NWC operation strategy should be considered.

### 6.2.5. Backward Compatibility

NWC operations should be applied in addition to the regular network behavior. Hence, nodes should be able to not support network coding (not only in forwarding the packets, but also in the caching mechanism). NWC operations should function alongside regular network operations. An NWC framework should be compatible with a regular framework in order to facilitate backward compatibility and smooth migration from one framework to the other.

## 6.3. In-network Caching

Caching is a useful technique used for improving throughput and latency in various applications. In-network caching in CCNx/NDN essentially provides support at network level and is highly beneficial owing to the involved exploitation of NWC for enabling effective multicast transmission [34], multipath data retrieval [10] [11], fast loss recovery [15]. However, there remain several issues to be considered.

There generally exist limitations in the CS capacity, and the caching policy affects the consumer's performances [26] [31] [32]. It is thus crucial for routers to determine which content objects should be cached and discarded. As delay-sensitive applications often do not require an in-network cache for a long period owing to their real-time constraints, routers have to know the necessity for caching received content objects to save the caching volume. In CCNx, this could be made possible by setting a Recommended Cache Time (RCT) in the optional header of the data packet at the publisher side. The RCT serves as a guideline for the CS cache in determining how long to retain the content object. When the RCT is set as zero, the router recognizes that caching the content object is meaningless. Conversely, the router may cache it when the RCT has a greater value. In NDN, the TLV type of FreshnessPeriod could be used.

One key aspect of in-network caching is whether or not routers can cache coded packets in their CS. They may be caching the coded packets without having the ability to perform a validation of the content objects. Therefore, the caching of the coded packets would require some mechanism to validate the coded packets (see Section 8). In the case wherein the coded packets have the same name, it would also require some mechanism to identify them.

### 6.4. Seamless Consumer Mobility

A key feature of CCNx/NDN is that it is sessionless, which enables the consumer and router to send multiple interests to different copies of the content in parallel, by using multiple interfaces at the same time in an asynchronous manner. Through the multipath data retrieval, the consumer could obtain the content from multiple copies that are distributed while using the aggregate capacity of multiple interfaces used. For the link between the consumer and the multiple copies, the consumer can perform a certain rate adaptation mechanism for video streaming [11] or congestion control for content acquisition [12].

NWC adds a reliability layer network to CCNx in a distributed and asynchronous manner, because NWC provides a mechanism for ensuring that the interests sent to multiple copies of the content in parallel retrieve innovative packets, even in the case of packet losses on some of the paths/networks to these copies. This obviously applies to consumer mobility events [11], wherein the consumer may connect between multiple access points (APs) before a consumer mobility event (make-before-break handoff). In the case of such a consumer mobility event, the consumer is first connected to the previous AP, then to both the previous and next APs, and then finally only to the next APs. With CCNx, the consumer only sends interests on the available interfaces. By combining NWC with CCNx/NDN, the requesting of coded

packets ensures that during the phase wherein it is connected to the previous and the next APs at the same time, it would not receive duplicate data, but does not miss out any content either. The consumer would receive additional degrees of freedom with any innovative packet it receives on either interface. From this perspective, an interest forwarding strategy at the consumer (and possibly router) for efficiently obtaining innovative packets should be considered for the consumer to achieve seamless consumer mobility.

## 7. Challenges

This section presents several primary challenges and research items to be considered when applying NWC in CCNx/NDN.

### 7.1. Adoption of Convolutional Coding

Several block coding approaches have been proposed thus far; however, there is still no sufficient discussion and application of the convolutional coding approach (e.g., sliding or elastic window coding) in CCNx/NDN. Convolutional coding is often appropriate for situations wherein a fully or partially reliable delivery of continuous data flows is required, and especially when these data flows feature realtime constraints. As in [36], on an end-to-end coding basis, it would be advantageous for continuous content flow to adopt sliding window coding in CCNx/NDN. In this case, the publisher is required to appropriately set coding parameters and let the consumer know the information, and the consumer is required to send interest (i.e., feedback information) regarding the data reception and/or decoding status. As CCNx/NDN advocates hop-by-hop communication, it would be worth discussing and investigating how convolutional coding can be applied in a hop-by-hop manner and its benefits. In particular, in the case wherein in-network recoding could occur at routers, both the encoding window and CS management would be required, and the corresponding feasibility and practicality should be considered.

### 7.2. Rate and Congestion Control

The Addition of redundancy using repair packets may result in further network congestion and could adversely affect the overall throughput performance. In particular, in a situation wherein fair bandwidth sharing is more desirable, each streaming flow must adapt to the network conditions to fairly consume the available link bandwidth. It is thus necessary that each content flow cooperatively implements congestion control to adjust the consumed bandwidth to stabilize the network condition (i.e., to achieve a low packet loss rate, delay, and jitter). From this perspective, although a router-supported

approach would be effective, an effective deployment scenario is required.

As described in Section 6.4, NWC can contribute to seamless consumer mobility by obtaining innovative packets without receiving duplicated packets through multipath data retrieval. It can be challenging to develop an effective rate and congestion control mechanism in order to achieve seamless consumer mobility while improving the overall throughput or latency by fully exploiting NWC operations.

## 7.3. Security

While CCNx/NDN introduces new security issues at the networking layer that are different from the IP network, such as a cache poisoning and pollution attack, a DoS attack using interest packets, some security approaches are already provided [22] [23]. The application of NWC in CCNx/NDN impacts the security mechanisms of CCNx/NDN.

CCNx/NDN is designed to prevent modification of the data packets; the data packet for a specific name can be self-authenticated, can be validated on the delivery path, and may also be cached at untrusted routers. NWC may bring up a security issue related to data integrity when performing in-network recoding, as attackers could inject invalid data packets, and fill the CSs at the routers with the invalid content objects (cache poisoning attack). On the assumption that each coded packet has the valid signature, the straightforward approach would comprises the routers verifying the signature within the coded packets in transit and only transmitting and storing the validated coded packets. However, as performing a signature verification by the routers may be infeasible at line speed, some mechanisms should be considered for distributing and reducing the load of signature verification, in order to maintain in-network cache benefits such as latency and network-load reduction.

In addition, to maintain the in-network cache efficiency, routers with CS should take caution when caching validated coded packets. As coded packets are unpopular in general use, they could be targeted by a cache pollution attack that requests less popular content objects more frequently to undermine popularity-based caching by skewing the content popularity. Denial of Service (DoS) attacks may also target the routers and/or the publisher performing NWC in order to impose a higher computation load owing to the NWC operations. NWC also offers a new surface of attack; if the coding vector is exposed at the network layer, it would have to be protected (and validated) in order to prevent modifications by an attacker (and allow for verification) on the path of the packet.

On the other hand, NWC could be used to mitigate privacy issues CCNx/NDN introduces. For instance, assuming that consumers can use multipath data retrieval and caching in CCNx/NDN with NWC, cache privacy and anonymity set for consumers can be improved in addition to caching performance owing to the diversity of the caching content objects along different paths.

In this context, it can be a challenge that coping with the security issues as low computation overhead as possible while facilitating the NWC operations in CCNx/NDN. From the perspective of both feasibility and practicability, more effective approaches with consideration of security would be required in order to accelerate the deployment of CCNx/NDN with NWC.

### 7.4. Routing Scalability

In CCNx/NDN, a name-based routing protocol without a resolution process streamlines the routing process and reduces the overall latency. In IP routing, the growth in the routing table size has become a concern. It is thus necessary to use a hierarchical naming scheme in order to improve the routing scalability by enabling the aggregation of the routing information.

It is required to enable consumers to efficiently obtain innovative packets using multipath retrieval in a fully distributed manner, and thus fully leverage NWC in CCNx/NDN to improve throughput or reduce latency. This would require some efficient routing mechanism to appropriately set the FIB and also an efficient interest forwarding strategy. Such routing coordination may create routing scalability issues. It would be challenging to achieve effective and scalable routing for interests requesting coded packets as well as to simplify the routing process.

## 8. Security Considerations

In-network recoding is a prominent operation of NWC; however, it may lead to cache poisoning attacks that inject invalid coded packets to the network. To address this issue, there exist some possible approaches. First, as a signature verification approach, the exploitation of multi-signature capability could be applied. This allows not only the original content publisher but also some routers responsible for in-network recoding to have their own unique signing key. Each router of the group signs newly generated coded packet in order for other nodes to be able to validate the data with the signature. The CS may verify the signature within the coded packet before storing it to avoid invalid data caching. Second, as a consumer-dependent approach, the consumer puts a restriction on the matching rule using only the name of the requested data. The

interest ambiguity can be clarified by specifying both the name and the key identifier (the publisher's public key digest) used for matching to the requested data. This KeyId restriction is built in the CCNx design [1]. Only the requested data packet satisfying the interest with the KeyId restriction would be forwarded and stored in the CS, thus resulting in a reduction in the chances of cache poisoning. Moreover, in the CCNx design, there exists the rule that the CS obeys in order to avoid amplifying invalid data; if an interest has a KeyID restriction, the CS must not reply unless it knows that the signature on the matching content object is correct. If the CS cannot verify the signature, the interest may be treated as a cache miss and forwarded to the upstream router(s). Third, as a certificate chain management approach (possibly without certificate authority), HopAuth could be used to establish a trustworthy data delivery path [28]. This approach adopts the hop-by-hop authentication mechanism, wherein forwarding-integrated hop-by-hop certificate collection is performed to provide suspension certificate chains such that the data retrieval is trustworthy.

Routers should also take caution when storing and retaining the coded packets (unpopular content objects) in the CS, as they could be targeted by cache pollution attacks. In order to mitigate the cache pollution attacks' impact on the in-network cache efficiency, the routers could check the request frequencies and store the coded packets with certain popularity to prevent the attacks. In addition, they could periodically evaluate the popularity or other properties of the cached content that are applied to the cache replacement mechanism.

The routers or publishers require careful attention to the DoS attacks aiming at provoking the high load of NWC operations by using the interests for coded packets. In order to mitigate such attacks, the routers could adopt a rate-limiting approach. For instance, they could monitor the PIT size growth for coded data per content to detect the attacks, and limit the interest arrival rate when necessary. If the NWC application wishes to secure an interest (considered as the NWC actuator) in order to prevent such attacks, the application should consider using an encrypted wrapper and a explicit protocol.

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