Name Resolution and Packet Forwarding in IP/NDN Mixed Environment

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***Abstract*—Information-centric networking (ICN), which can efficiently transfer contents such as IoT data by transferring request packets (Interests) with the name of contents, is being studied as a next-generation network. NDN (named data networking) is one of the architectures of ICN, which is actively studied. When NDN is put to practical use in the real world, in the process of popularization of NDN, there is a mixed environment of autonomous system (AS) of IP and AS of NDN, so how to transfer packets is a problem. In IP-AS, the communication partner is specified by IP address and the packet is exchanged. However, in NDN-AS, the response data packet is requested by Interest, so the communication partner is not specified by name resolution at the start of communication. Therefore, in order to realize communication between ASes using different networks, it is necessary to realize mutual conversion of IP and NDN packets. In order to solve this problem, a method for communication between IP-NDN has been proposed by installing a gateway (GW) with packet translation function on the boundary link between different autonomous systems and rewriting the packet header. However, in order to rewrite the header of a packet, it is necessary to manage the name and IP address of contents corresponding to the IP address and the name of contents written in the header of each packet by packet translation GW. In this paper, we propose a packet transfer method to use the packet translation method by packet translation GW in an environment where actual IP and NDN are mixed. We also evaluate the effect of the proposed method on the required packet transfer delay by computer simulation, and show that NDN may be effective for efficient content distribution even in an environment where IP and NDN are mixed.**

I. Introduction

TCP/IP used in the conventional Internet uses DNS (domain name system) to resolve the name of the data distribution host (Publisher) at the start of communication, and to obtain the IP address to send and receive data from Publisher. However, most of the current purpose of Internet use is to distribute digital contents such as Web and video, which is very different from that at the time when TCP/IP was developed. Therefore, ICN (information-centric networking) [7][8][16] is being studied as a next-generation network to realize efficient content distribution. ICN does not perform name resolution at the start of communication, transfers Interest by the name of the content, and caches the content distributed from Publisher in the router. In ICN, the router can understand the content name from the information written in the header of Interest. Therefore, when the cache of the requested content exists in the router on the route to which Interest is transferred, content is distributed efficiently using the cache from the router. As a network architecture to realize ICN, NDN is actively studied, and this paper assumes NDN (named data networking) as the architecture of ICN.

In NDN, the routing of a packet is determined by two tables, FIB (forwarding information base) and PIT (pending Interest table). The FIB is a table for checking the next hop to which the Interest should be forwarded, and the forwarding route of the Interest is determined by referring to this table. When the content is published on the network, Publisher advertises the name of the content. The advertisement of the content name spreads throughout the network by the router receiving the advertisement re-advertising to the neighboring router, and the FIB is updated when the advertisement of the content name is received from the neighboring router. This process sets up the FIB so that the Interest is forwarded to Publisher. The PIT is a table that records the neighboring router which is the forwarding source of the Interest. When the data packet is returned in response to the Interest, the data packet is forwarded to the forwarding source of the Interest recorded in the PIT, and the forwarding route of the data packet is determined so as to go back to the route in which the Interest was forwarded.

Since NDN is introduced to each AS by the network provider who operates each AS, it is unrealistic to replace all existing IP networks with NDN, and it is assumed that an environment where IP-AS and NDN-AS are mixed is constructed. In such an environment, a packet transfer method between IP and NDN networks is required. In order to realize communication between IP, which transfers packets based on IP address, and NDN, which transfers packets based on content name, it is necessary to exchange IP packets and NDN packets by rewriting packet headers. Therefore, we proposed a method to realize packet transfer between IP-NDN by installing a gateway (GW) with a packet translation function on the link that is the boundary between IP-AS and NDN-AS [1]. However, in [1], although we assumed that NRS (name resolution service), which is the server that manages the correspondence between IP address and content name, was used, we did not provide how the NRS gave the correspondence between IP address and content name.

Therefore, in this paper, we propose a method to realize packet transfer between IP and NDN using GW by providing information necessary for packet translation to GW when the host (consumer) requests content instead of preparing the NRS which manages the correspondence between IP address and content name. In this new method, packet transfer is completed solely by the Consumer and the packet translation GW, and it doesn't require any new external systems other than the GW. One advantage of enabling global connectivity between IP-AS and NDN-AS only through GWs is that this approach can also be applied to ICN-based IoT services (ICN-IoT) [9] and to cache data management using NDN within Low Earth Orbit satellite networks [10]. Accordingly, in the proposed method, an independent NDN network can be constructed with compatibility to IP without requiring any additional external systems other than the GW, thereby enabling flexible operation of various NDN-based services. This proposed method is not intended for any specific protocol such as HTTP or FTPS, but rather aims to serve as an alternative to the existing Internet. We also evaluate the effect of this method on the required packet transfer delay by computer simulation and show that NDN may be effective for efficient content distribution even in an environment mixed with IP. By evaluating global communication that spans across ASes rather than performance within a limited domain, its effectiveness can be demonstrated in a more realistic manner.

Section II describes the related works, and Sections III and IV describe the proposed method. Section V describes the performance evaluation by computer simulation, and Section VI summarizes this manuscript.

II. Related Works

In [1], a method to realize packet transfer between IP and NDN was proposed by using GW with packet translation function in the transition period from IP to NDN. Furthermore, an architecture of packet translation GW was proposed and its throughput was analyzed experimentally. By this numerical evaluation, it was confirmed that the throughput was improved by the deviation of content popularity. As a method to realize a mixed environment of IP and NDN, various approaches such as dual-stack approach [3] and NDN deployment method using existing network as overlay network [5] [14] have been proposed in addition to packet translation GW. There are also a variety of proposed coexistence methods, including the use of hICN technology, such as that proposed by Giovanna Carofigliog et al [15].

In particular, the overlay method is well studied, but there are problems such as the need to prepare a new layer for providing NDN over IP and the overhead of processing such as packet encapsulation. The advantage of using packet translation GW is that the upgrade cost of network hardware required to transition from IP to NDN is small [2], and no extra changes to the existing network are required because pure NDN coexists with the conventional IP network. In this paper, we propose a coexistence method of IP and NDN which is expected to have these advantages different from the overlay method.

When considering the problem of introducing NDN in a global environment, how to realize a mixed IP-NDN environment is an important issue, as discussed in the inter-domain routing method in an environment where NDN-AS exists [11][12].

A. Overview of IP-NDN Translation GW

In this section, we outline the GW, i.e., DINT-GW (Dual-channel IP to NDN translation gateway), proposed in [1]. Figure 1 below shows the configuration of DINT-GW.

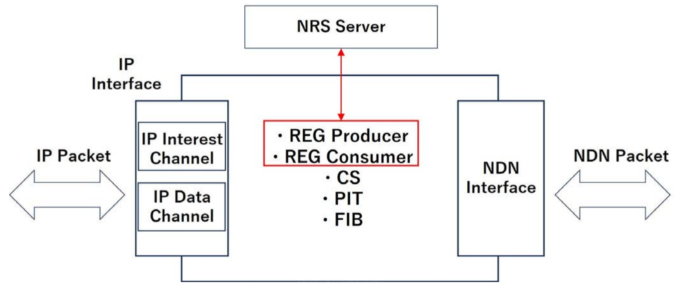

Fig. 1. Components of packet translation gateway

The proposed DINT-GW has an IP interface for IP communication and an NDN interface for NDN communication. When exchanging IP packets, it has two channels, an IP Interest Channel and an IP Data Channel, and different IP addresses are used for each channel to identify whether the packet being transferred is an Interest packet or a data packet. REG (register table) is used to store the correspondence between the content name and the IP address in DINT-GW. In IP networks, each host may play both roles of Consumer and Producer (Publisher), so there are two types of REG: REG Producer and REG Consumer. Packet translation is performed based on the correspondence between the content name and the IP address stored in this REG. If the correspondence between the content name and the IP address cannot be resolved by REG, NRS is consulted.

Content Store (CS), PIT, and FIB of DINT-GW have the same roles as those of NDN routers. CS has the function of caching content data, PIT is used to record the destination of Interest transfer in neighboring routers, and FIB is used to determine the destination of Interest transfer. The packet translation GW assumed in this paper is equivalent to DINT-GW. However, NRS and REG are not used in consideration of the problem of matching content names with IP addresses.

III. Preprocessing Before Packet Forwarding

In the packet transfer method between IP and NDN using GW proposed in this paper, two processes are required before packet transfer: FIB setting to transfer Interest to packet translation GW and registration of contents on NDN-AS in DNS with IP address of GW. The FIB entry for an NDN router contains only route information for publishers that exist on the NDN-AS to which it belongs and the NDN-AS to which it is connected. Therefore, when an NDN-Consumer forwards a packet for content published on the IP-AS with only the name of the content, it is impossible to determine the next hop in the FIB of the NDN router. To solve this problem, FIB setting to transfer Interest to packet translation GW is required. In this paper, when an Interest with a content name not present in the FIB is forwarded, the router is configured to forward the packet to the route to the nearest packet translation GW. When Interest reaches packet translation GW, packet conversion GW converts NDN-Interest to IP-Interest to realize packet transfer. The process of packet forwarding is described in Section IV.

Also, when IP-Consumer requests contents on NDN-AS, name resolution is impossible because NDN contents do not have IP address. To solve this problem, it is necessary to register contents on NDN-AS in DNS with IP address of GW. When Publisher publishes new contents on NDN-AS, advertisement of contents name is carried out in NDN-AS where Publisher exists. This advertisement is also carried out to packet translation GW. When the packet translation GW receives advertisement of contents name, it adds a new entry in DNS with the contents name as domain and IP address of packet translation GW itself as IP address corresponding to the domain. By this process, when the IP-Consumer requests the contents on the NDN-AS, the IP address of the packet translation GW is provided from the DNS. The GW translates the IP-Interest and forwards it to the NDN-AS. This translation method is also described in Section IV.

IV. Packet Forwarding Process

In the packet transfer method between IP and NDN using GW proposed in this paper, packet translation GW rewrites the header of a packet when transferring packets between IP and NDN. GW creates a new header for the other protocol, including the destination part. This header is used to create a new packet by rewriting the data of the original packet, and the packet is translated. In this header rewriting process, packet translation GW needs to know the IP address and the name of the contents to be written in the header. Therefore, packet translation GW manages the information necessary for header rewriting such as the name and IP address of the contents requested by each Consumer sending Interest in a table called RIMT (rewriting information management table).

Information required for header rewriting is collected in RIMT by DNS and information provided by each consumer, and the mutual translation of IP and NDN packets is realized. RIMT is updated when packet translation GW is used for Interest transfer, but the information that needs to be managed in RIMT differs depending on whether the consumer is transferring NDN-Interest or IP-Interest, and two types of RIMT are required: one for IP-Consumer and one for NDN-Consumer.

The two types of information required for the IP-Consumer RIMT are the IP address of the IP-Interest transfer source host and the name of the requested content. In this paper, these two are collectively referred to as ICII (IP-consumer Interest information). The three types of information required for the NDN-Consumer RIMT are the IP address of the requested content, the name of the requested content, and the port number used to transfer the converted IP-Interest. In this paper, these three are collectively referred to as NCII (NDN-consumer Interest information).

Hereinafter, the processing for transferring the Interest from the IP-AS to the NDN-AS is described in Section IV-A, the processing for transferring the Interest from the NDN-AS to the IP-AS is described in Section IV-B, and the processing for passing the packet through multiple GWs is described in Section IV-C.

A. Forwarding Interest from IP-AS to NDN-AS

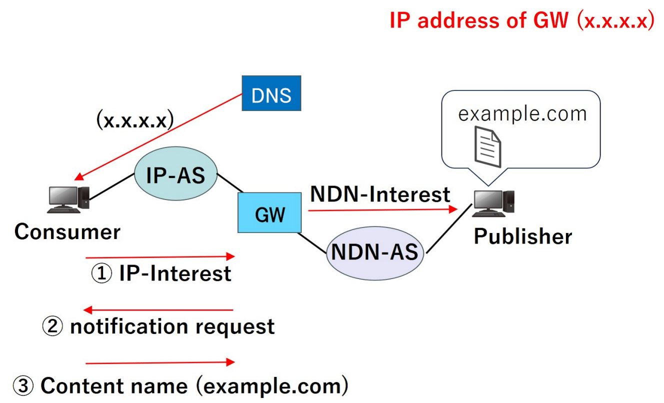

Fig. 2. Interest packet forwarding from IP-AS to NDN-AS and Data packet forwarding from NDN-AS to IP-AS

When content is published in NDN, it is usually named like a URL [7][13]. If an IP-Consumer wants to access content published on an NDN-AS named ”example.com”, it will try to get the IP address of ”example.com” from DNS. However, since ”example.com” itself does not have an IP address, the IP-Consumer obtains the IP address of GW connected to NDN-AS in which ”example.com” is published. When the IP-Interest is transmitted to the GW, the GW requests the IP-Consumer to notify the requested content name (meaning ”example.com”). When the requested content name is obtained from the IP-Consumer, an NDN-Interest for acquiring the content requested by the IP-Consumer is created using the name and transferred to the NDN-AS. At the same time, the ICII of the IP-Interest is registered in the IP-Consumer RIMT. NDN-AS searches the FIB for the NDN-Interest destination with the name ”example.com” and forwards the packet. When the packet reaches the Publisher that publishes ”example.com” or the NDN router that has a cache of ”example.com,” it sends back an NDN-Data packet. Returned NDN-Data packets are translated at GW as IP-Data packets. At this time, since the name of the returned content is ”example.com,” the GW searches the IP-Consumer RIMT for the IP address of the IP-Consumer requesting ”example.com” and uses the identified IP address as the destination of the IP-Data packet. Thus, the translated IP-Data packet is returned to the IP-Consumer. When the session is completed, this ICII information is deleted.

B. Forwarding Interest from NDN-AS to IP-AS

When an NDN-Consumer accesses a content named ”example.com” published in a certain IP-AS, it transmits an NDN-Interest with the name ”example.com.” However, there is no forwarding destination entry of ”example.com” in the FIB because the information of the contents published in the IP-AS is not advertised in the NDN router. Therefore, such NDN-Interest is forwarded to the nearest GW. When GW receives an NDN-Interest, it uses the content name of the Interest to use DNS. If the name resolution fails, it is determined that the request is for non-existent content, and the packet

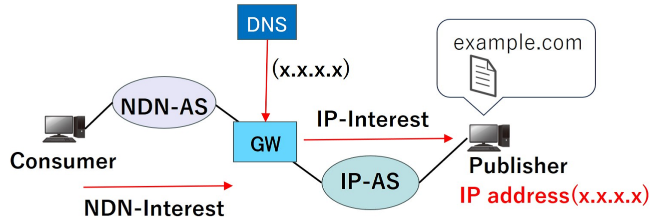

Fig. 3. Interest packet forwarding from NDN-AS to IP-AS and Data packet forwarding from IP-AS to NDN-AS

is rejected. If the name resolution succeeds, an IP-Interest for acquiring the content requested by NDN-Consumer is created using the acquired IP address, and is forwarded to the IP-AS. When the IP-Interest is transmitted to the IP-Publisher of the content source, an IP-Data packet of ”example.com” is returned. Returned IP-Data packets are translated at GW as NDN-Data packets. At this time, the NCII in which the source IP address of the IP-Data packet returned to the GW and the port number used match the IP address and port number recorded in the NDN-Consumer RIMT is searched, and the translated NDN-Data packet is returned to the NDN-Consumer using the name of the content specified from the search result. In this way, the translated NDN-Data packet is returned to the NDN-Consumer. When the session is completed, this NCII information is deleted.

C. Packet Forwarding Via Multiple Gateways

When packet translation GW is used multiple times, such as when an IP-AS communicates with another IP-AS via an NDN-AS or when an NDN-AS communicates with another NDN-AS via an IP-AS, packet transfer can be realized by applying and repeating the processing described in Sections IV-A and IV-B.

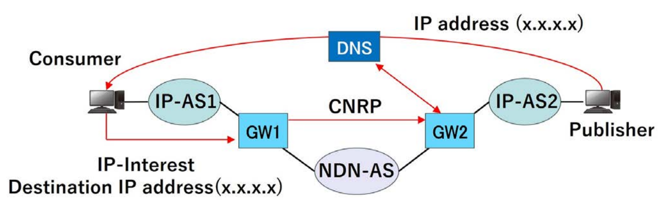

Fig. 4. Packet transfer between IP-AS across NDN-AS

Figure 4 shows the processing added by using the packet translation GW multiple times in the procedure of transferring an Interest packet and a data packet from an IP-AS to another IP-AS via an NDN-AS. When the IP-Consumer belonging to IP-AS1 accesses the contents of the IP-Publisher belonging to IP-AS2, if the IP-Consumer performs name resolution by DNS, the IP-Consumer acquires the IP address of the IP-Publisher. This paper assumes that an inter-domain routing method such as NBGP [11] is used and inter-AS routes are determined regardless of the protocol adopted by each AS. Therefore, the router of IP-AS1 forwards IP-Interest to IP-Consumer, but uses GW1 to pass through NDN-AS. Since the destination IP address of the received IP-Interest is different from the IP address of the GW1 itself, the GW1 judges that this IP-Interest is not for accessing the content existing in the NDN-AS, but is transmitted for relaying to another IP-AS. Therefore, GW1 transmits a packet called CNRP (Content Name Relay Packet) for transmitting a request content name between GWs to GW2 connected to the IP-AS2. The identification name of the GW as the destination is used for the header of the CNRP, and the identification name of the GW is added to the name of the request content. GW2 obtains an IP address from DNS using the content name transmitted by CNRP and creates an IP-Interest. In this way, each GW can function as a substitute consumer by allowing the GWs to share the information of the requested content name when passing through the NDN-AS. When the NDN-Data packet acquired by the GW using CNRP is translated into an IP-data packet and returned, the IP address of the return source is not the address of the GW itself, but rewritten into the IP address of the original request content and returned.

V. Performance Evaluation

A. Evaluation model

We evaluated the packet transfer delay caused by the proposed method on the network by computer simulation using actual inter-AS topology data [4]. Since the data of [4] is too large for simulation, we reduced the number of ASes by the sampling method used in [6]. The AS topology used in this simulation consists of a hierarchical structure consisting of a high-order AS with a large number of connection paths acting as a superhub node, and a large number of low-order with a small number of connection paths. For the inter-AS topology after sampling, we obtained the shortest path between any node pairs by the Dijkstra method, and we investigated the required packet transfer delay in the case of communication using the shortest path. The lower the order of AS, the greater the benefit for network providers to introduce NDN [6]. However, because high-degree ASes are used in more inter-AS paths, the overall delay reduction effect is greater when high-degree ASes introduce NDN. Therefore, we consider two scenarios: Scenario 1, where only 70% of ASes with a degree of 2 or less adopt NDN, and Scenario 2, where the top 5% of ASes by degree and 70% of ASes with a degree of 2 or less adopt NDN.

In the proposed method, information for rewriting packet headers is stored in RIMT. The amount of information that can be recorded in the RIMT depends on the hardware resources of each GW, and when Interests are excessively forwarded, the RIMT becomes unavailable. This means GW is temporarily unavailable, causing packet loss. When packet loss occurs, the packet translation GW cannot record Interest information in RIMT, so it is necessary to request the consumer to retransmit the Interest. This processing may cause large packet transfer delay. In the computer simulation, the packet transfer delay is assumed to be proportional to the number of ASes used as each communication path, and the average RTT (round trip time) is assumed to be about 296 ms. The average RTT used in the computer simulation is the average value of the packet transfer delay measured from the RIPE Atlas [17] terminals located at universities selected from multiple regions. The locations of the RIPE Atlas terminals used as the measurement targets are Kyoto University (Japan), Boston University (United States of America), Stanford University (United States of America), Rio Grande do Sul University (Brazil), Universidad Carlos III de Madrid (Spain), University of Hamburg (Germany), and Nelson Mandela University (South Africa). This measurement was made by pinging each RIPE Atlas terminal and was conducted on May 23, 2024. In the inter-AS topology used in the computer simulation, the average number of ASes between each incoming and outgoing AS pair sd is about 4.43, so the packet transfer delay for each AS is assumed to be about 33.4 ms. In the simulation of packet transfer delay, we investigated how the value assumed to be an average RTT of 296 ms in the case of IP only changes in a topology with an AS in which NDN is introduced.

The packet transfer delay considered in this paper is only the transfer time of interest and data packets, and does not include the computation time such as the use of DNS and packet header rewriting by the packet translation GW. This is because computation time depends greatly on hardware performance. The actual hardware used is assumed to vary by network provider, and it is difficult to assume a reasonable value for system utilization time. In Section V-B, the number of packet translation GWs passed between each incoming and outgoing AS pair sd is described, and the simulation result of the packet transfer delay is evaluated in Section V-C.

B. Number of GWs Passed

When Interest is transferred between each incoming and outgoing AS pair sd, if a cache hit occurs on the NDN-AS that is passed through, the content is distributed from that cache. Therefore, the Interest is only forwarded a shorter distance than the original forwarding path. When the transfer path of Interest is shortened, the utilization of packet translation GW also decreases. The smaller the number of packet translation GW paths between sd is, the smaller the average packet loss is. Therefore, the number of passages of packet translation GW is an important factor when considering the effect of the proposed method on communication delay. Therefore, we conducted a computer simulation to investigate the number of packet translation GW paths considering the shortening of the transfer path of Interest. Three cases were assumed as the value of the cache hit rate in each NDN-AS.

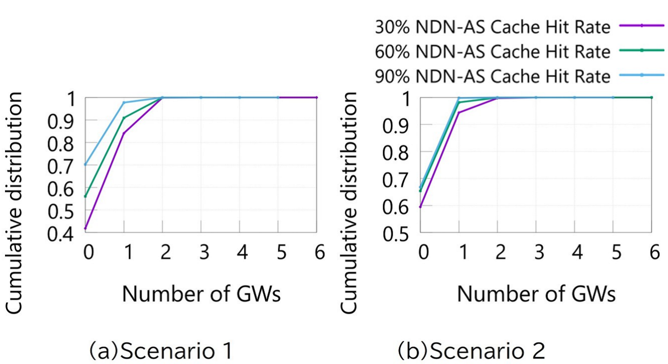

Fig. 5. Cumulative distribution of GW counts for each path for Scenario 1 (left) and Scenario 2 (right)

Figure 5 show the cumulative distribution of the number of packet translation GWs that pass through each AS pair sd in Scenario 1 and Scenario 2, respectively. In Scenario 2, NDNs are introduced in a part of the high-order AS that plays a hub role, and the effect of shortening the forwarding path of Interest is large. Even when the cache hit ratio is 30%, the probability of requiring multiple packet conversions is less than 10%, and the overhead is suppressed. Even in Scenario 1, the number of packet translation GWs passing through 2 or less accounted for more than 99% of the routes, and it was confirmed that the utilization rate of packet translation GWs was kept at a low value, although not as high as in Scenario 2.

C. Packet Transfer Delay

The packet transfer delay is defined as the time required from the sending host to the reception of the data packet for the request packet. The factors that affect the packet delay in the proposed method are both factors that reduce it and factors that increase it. The factor that reduces the packet delay is the effect of shortening the communication path by introducing NDN. On the other hand, the two factors that increase the packet delay are the processing in which the IP-Consumer reports the request content name to the packet translation GW described in the section IV-A and the processing in which packet loss occurs in the packet translation GW described in the section V-A. The packet translation GW uses two tables, ICII and NCII, to temporarily store the IP address and content name. However, because the size of these tables is finite, when the memory capacity is insufficient, the translation information cannot be recorded in these tables. In this case, the sending host has to send the request packet again. In this section, we describe the evaluation results of the effects of two conflicting factors on the packet delay time when the loss rate in these tables is varied.

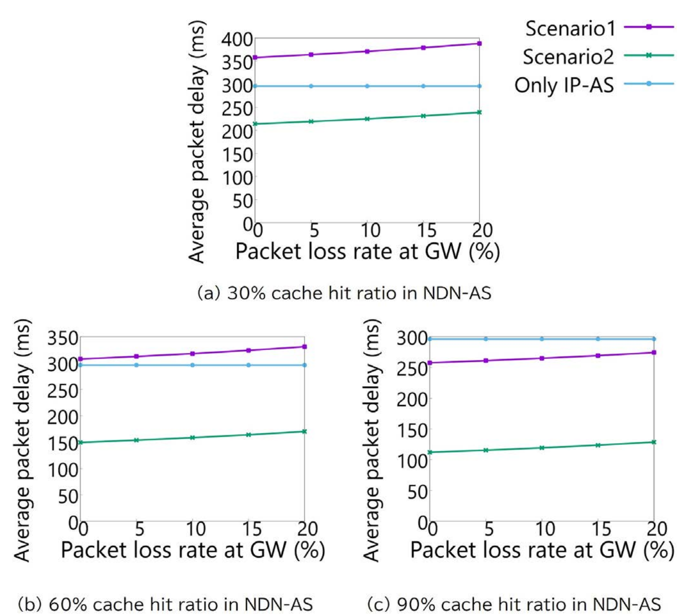

Fig. 6. Average packet delay

Figure 6 plots the average packet transfer delay against the packet loss rate in GW when the cache hit rate of each NDN-AS router is 30%(top), 60%(bottom left), and 90%(bottom right), respectively. Scenario 2 always achieved smaller average packet transfer delay than IP only. This is due to the fact that NDN is introduced into the AS that is frequently used as an Interest transfer path, which increases the probability that a cache hit occurs at an early stage of Interest transfer. On the other hand, the increase in the average packet delay due to the packet loss rate is larger in Scenario 1 than in Scenario 2 because the number of packet translation GWs is larger than in Scenario 2. In addition, because NDN is not available in the high-order AS that is used as a path between many incoming and outgoing AS pairs sd, the reduction effect of packet transfer delay is small when the cache hit rate is 30% and 60%, and the average packet delay increases compared to the case of communication using IP only. From the above, we confirm that the introduction of NDN into the high-order AS is effective in reducing the overall average packet delay.

VI. Conclusion

In this paper, we propose a packet transfer method between IP and NDN using packet translation GW. We prepare the Interest to be transferred to the packet translation GW when communication is carried out between different networks by pre-packet transfer processing, and manage the information necessary for rewriting the header by RIMT during packet transfer. Interconversion between IP and NDN packets is realized by this two-step processing. We also evaluate the number of packet translation GWs and average packet delay by computer simulation when communication is carried out in a mixed IP and NDN topology.

The proposed method has a problem that the packet delay may become very large when the packet loss rate in the packet translation GW is high. When the packet loss occurs, the packet translation GW requests the consumer to retransmit and retries the communication. This is because the probability of successful transfer of Interest without packet loss for each retransmission attempt follows a geometric distribution, and the probability of repeated packet loss in the same packet translation GW increases when the packet loss rate is high. In the proposed method, the transfer rate of Interest greatly influences the packet loss rate in the packet translation GW, because ICII or NCII must be recorded for all transferred Interests. The number of ICII and NCII that can be recorded in the packet translation GW is to be studied in the future to realize the packet loss rate that can be expected to reduce the packet transfer delay when the proposed method is used.

In addition, the computer simulation in this paper adopts the path with the minimum number of hops between each incoming and outgoing AS pair sd determined by the Dijkstra method as the packet transfer path. However, since the path is actually shortened by using the cache of NDNs, the use of the packet transfer path which increases the utilization rate of NDNs may increase the effect of shortening the packet transfer path length and decrease the RTT. Therefore, the optimal inter-AS routing method considering the path shortening effect of the proposed method will be studied in future.

Acknowledgements

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