ICN 2026

The Twenty-Fifth International Conference on Networks

ISBN: 978-1-68558-392-7

May 24 - 28, 2026

Venice, Italy

ICN 2026 Editors

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ICN 2026

Forward

The Twenty-Fifth International Conference on Networks (ICN 2026), held between May 24-28, 2026 in Venice, Italy, continued a series of events organized by and for academic, research and industrial partners.

We solicited both academic, research, and industrial contributions. We welcomed technical papers presenting research and practical results, position papers addressing the pros and cons of specific proposals, such as those being discussed in the standard fora or in industry consortia, survey papers addressing the key problems and solutions on any of the above topics short papers on work in progress, and panel proposals.

The conference had the following tracks:

- Communication
- Networking
- Advances in Software Defined Networking and Network Functions Virtualization
- Next generation networks (NGN) and network management
- Computation and networking
- Topics on Internet Censorship and Surveillance

We take here the opportunity to warmly thank all the members of the ICN 2026 technical program committee, as well as all the reviewers. The creation of such a high quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to ICN 2026. We truly believe that, thanks to all these efforts, the final conference program consisted of top quality contributions.

We also thank the members of the ICN 2026 organizing committee for their help in handling the logistics and for their work that made this professional meeting a success.

We hope that ICN 2026 was a successful international forum for the exchange of ideas and results between academia and industry and to promote further progress in the field of networks. We also hope that Venice provided a pleasant environment during the conference and everyone saved some time to enjoy the historic charm of the city.

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A Study on Delay-Sensitive Information-Centric Wireless Sensor and Actuator/Actor Networks

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***Abstract*—This paper presents an information-centric wireless sensor and actuator network for delay-sensitive applications. In particular, the delay (data freshness) metric based on the age of information is proposed. The traditional metrics in host-centric (server-client) networks are not effective because the information-centric design emphasizes content (named) data. This paper presents the blueprint of the proposed scheme and a preliminary evaluation based on computer simulations.**

Keywords—age of information; information-centric networking; wireless sensor and actuator/actor networks

I. INTRODUCTION

The emerging, reliable, and delay-sensitive Wireless Sensor Networks (WSNs) and Wireless Sensor and Actuator/Actor Networks (WSANs) technologies are playing an essential role in the future Internet of Things (IoT) based on wireless communications and networks for smart-city deployments, such as smart agriculture and smart industry (factories). These application services include environmental monitoring, remote sensing, and drone/robot controlling. In such scenarios, a variety of physical devices, such as temperature sensors, moisture detectors, pH sensors, and Global Positioning (Satellite) System (GPS) modules, are distributed throughout the field to gather real-time environmental data. WSANs are composed of spatially distributed controllers, sensors, and actuators communicating via wireless channels, as well as the physical processes to be controlled. In other words, WSAN is a WSN with several actuators/actors. In the spotlight on sensing data in industrial and agricultural node devices, monitoring and control data should be forwarded and processed in real time (live streaming). Then the data are collected and analyzed on a central cloud server, affecting critical tasks, such as manufacturing, product-quality management, stock monitoring, and irrigation scheduling, to improve efficiency and safety, enabling task sharing and decision-making [1][2].

For the deployment of WSNs and WSANs, the data should be exchanged reliably, delay-sensitively, and efficiently across open, autonomous, and distributed areas with minimal human involvement. In such a networking environment, Information-Centric Networking (ICN) is a promising future network architecture that shifts the networking model from host locations to transmitted information [3]. Traditional host-centric network schemes generally exchange data based on addresses, such as Internet Protocol (IP) addresses, while ICN names the data, and named data are delivered directly based on their properties (names). In some traditional networks, such as content delivery networks, data is copied and stored across network nodes, and cached data is further used for data retrieval. ICN natively enables in-network caching scheme to share data within a peer-to-peer network. Furthermore, adopting an ICN mechanism with a multi-route delivery mechanism can remove the single-route disruption failure issue and improve content delivery effectiveness. The ICN frameworks have been recently investigated in IoT platforms, which are also called Information-Centric WSNs (ICWSNs) [4]. This applies not only to WSNs but also to Information-Centric WSANs (ICWSANs).

Let us now reconsider the characteristics of WSNs versus WSANs. In Sensor Nodes (SNs), sensing data is sent via the network (an open-loop system). In contrast, in Sensor and Actuator/Actor Node (SANs), sensing (and control) data is sent, and the SAN replies with the control command data (a closed-loop system). In the study of WSANs, most research focuses on control perspective. It oversimplifies wireless network models that do not capture key parameters of a practical wireless communication system, such as latency, data rate, and reliability [5][6]. For real-time and streaming data transmissions, on the receiver-side nodes, the data must be updated promptly to ensure its freshness, as outdated data can lose its value to users and be unsuitable for actuator controls. Note that this makes WSANs more critical than WSNs because they perform critical actuator/actor controls based on the backward data from the cloud or edge-side nodes.

This paper also focuses on how delay should be considered when adopting an ICN design instead of a traditional host-centric network design. On the conventional platform, data is provided by nodes identified by their addresses; thus, the delay metric can be measured as the round-trip time using the Internet Control Message Protocol (ICMP)-compliant ping command. However, since ICN manages data by name, it does not explicitly determine which node will respond; therefore, its conventional metrics are not helpful. Note that ICN data retrieval does not necessarily require the source node to be data-providing, i.e., the data-requester-side node broadcasts a data-request (so-called interest) message to the network, and the node that stores the targeted data and closest to the requester answers.

In this study, to quantify data freshness, we propose a novel ICWSN/ICWSAN scheme that uses the Age of Information (AoI) [7] as a delay metric. The proposed scheme is expanding based on the previously developed ICWSN platform [8]. The contribution of this paper is to expand the AoI concept to ICWSANs, which has not been investigated in previous studies. AoI is typically defined as the time elapsed since the data is generated. For the types of related indicators, there have been slightly different definitions, such as age of synchronization (the time elapsed from when the transmitter-side node updates data until the user receives the most recent data), effective AoI (the AoI with active information updates for users), age of incorrect information (the time interval from the receiver-side node's last receipt of the most recent data from the transmitter-side node until the current time), and age of outdated information (the time difference between the current time and the time when the data at the transmitter-side node initially becomes outdated). In this paper, the blueprint of the proposed scheme is presented, including an integration of AoI for ICWSANs, its modelization, and a preliminary evaluation using computer simulations to demonstrate the effectiveness of the proposed scheme.

The remainder of this paper is organized as follows. Section II discusses related work. Section III provides a formulation of the proposed scheme. Section IV presents the numerical results and discussion. Finally, Section V concludes this paper with a summary and mention of future work.

II. Related Work

Nagaraj et al. [9] investigated an industrial automation control system based on ICN and identified the requirements of industrial networks. The system focused on the application of ICN to WSANs for Industry 4.0, which aligns with this paper's direction. Zhang et al. [10] investigated a mobile edge computing system for periodically collecting data, given the limited energy and computational capabilities of node devices. The evaluation was analyzed using the AoI criterion for WSNs. Zhao [11] investigated an unmanned aerial vehicle-assisted WSNs, in which a UAV periodically collected sensing data. The evaluation of the system used an extended AoI, named the age of multi-sensor association information metric, incorporating multi-source and up- and down-link aspects for a certain type of WSANs. Huang et al. [12] investigated the trade-off between latency and reliability in packet-length control for WSANs. The author pointed out that if a message is encoded into a longer codeword, its reliability is improved at the expense of longer delay from the channel-encoding theory. Basnayaka et al. [13] analyzed a relay network with AoI for short packet communication to meet delay-sensitive requirements.

III. System Description

Figure 1 shows the network model of the proposed scheme. The network structure here is the same as the ICWSN framework [8], which is extended specifically from ICWSNs to ICWSANs. The network nodes consist of Sensor Nodes (SNs), Sensor and Actuator/Actor Nodes (SANs), Relay Nodes (RNs), and Private Base Station (PBS). The SN acquires information, e.g., a sensor measurement (text-based data) or an image captured by a camera (visual data). These data include ambient noise, vibrations, and control for industrial scenarios and environmental monitoring,

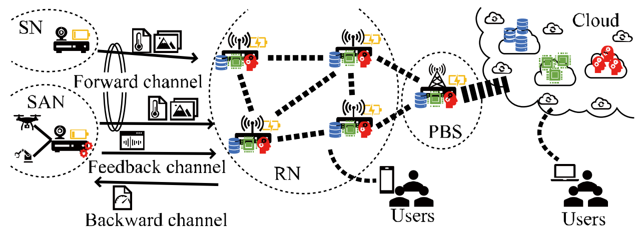

Figure 1. Network model of proposed scheme

temperature, and humidity for agricultural scenarios. In SANs, the sensor and the actuator/actor are co-located at the same node to simplify exposition, but this need not be the case in reality. The observed data are packetized, locally processed, and prepared for transmission as sensing data, and then they are committed to the network.

The WSAN is a distributed, closed-loop feedback control system that communicates via a shared wireless link. Therefore, in wireless links for data transmission, WSNs have only a forward channel (uplink) for sensing data, whereas WSANs additionally have a feedback channel (uplink) and a backward channel (downlink) for actuator/actor command data. Note that this paper assumes that SN and SAN can access the nearest RN with a single hop. The sensing data are forwarded to PBS, which coordinates the local area, via an edge-side network composed of multiple RNs operating as a mesh. PBS includes RN functionality and a proxy for external networks, and a portion of the sensing data is shared with the cloud if necessary. There are two types of users: internal network users and external network users. The former accesses the nearest RN and exchanges the data according to ICWSN/ICWSAN procedures, while the latter can only share and access the data and control via the cloud.

Figure 2(a) illustrates the procedure of the proposed scheme for collecting and retrieving the sensing data. To shift computational functions, such as analysis and command determination, from the cloud to the edge-side nodes, the RN is equipped with a functor (and a queue). SNs and SANs periodically generate data and send it to the nearest RN. In particular, SANs' data is sent to RN, PBS, and cloud servers, and feedback data is sent back to control the systems appropriately. In contrast, the sensing data are retrieved by users as needed. The user commits a data retrieval request (interest) to the network, and the data delivery is completed when the nearest node that holds the requested data returns a response. In this case, the data freshness is modeled as follows.

Supposing K SNs/SANs are distributed in an ICWSN or ICWSAN field. The n th SN/SAN ($n = 1,2,\cdots,N$) sends the sensing data periodically, which is given by

$$x_{t+1,n} = ax_{t,n} + bu_{t,n} + w_{t,n} \tag{1}$$

where $x_{t,n}$ is the sensing data via the forward and feedback channels, $u_{t,n}$ is the control data via the backward channel, and $w_{t,n}$ is the (thermal and ambient) noise in the device and channel at time t. a and b are constant values that depend on the environment and device.

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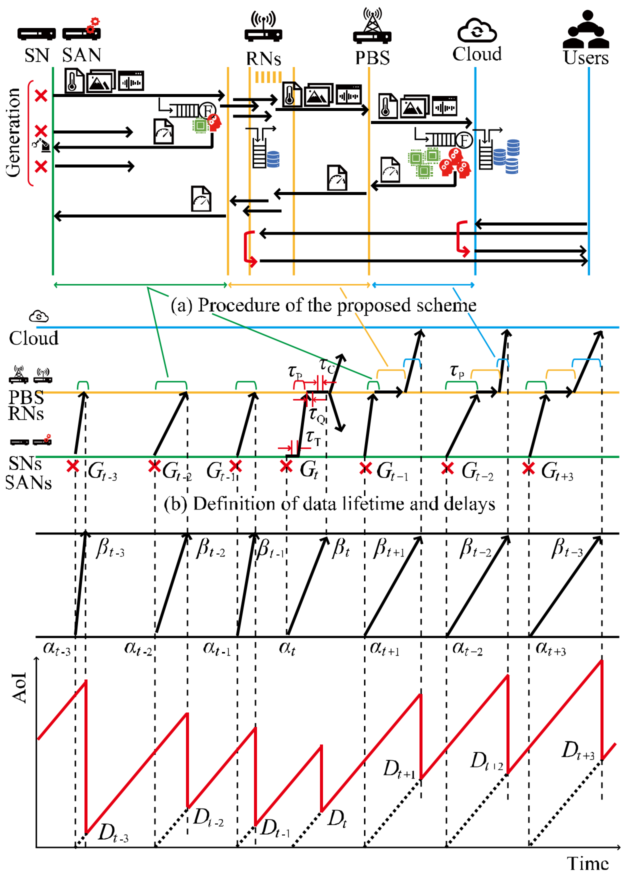

(c) Definition of age of information (AoI)

Figure 2. Prodecure of proposed scheme and definition of AoI metrics

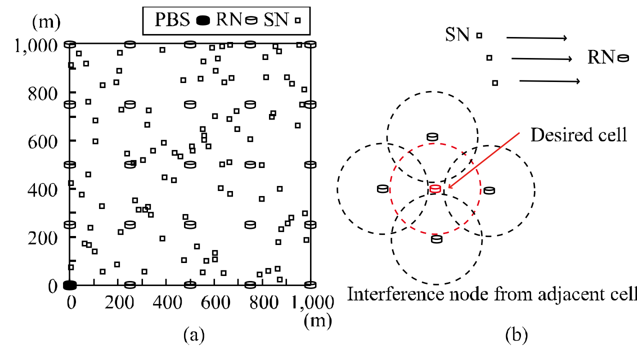

Figure 3. Simulation environment

TABLE I. SIMULATION PARAMETERS

Terms		*Values*
Size of observation field in ICWSN/ICWSAN		1 km^2
Number of SNs, N		10,000 /km^2
Number of RNs (including a PBS), K		25
Number of chennels	Microwave-band link	24
	mmWave-band link	108
Coverage range		200 m
Delay	Transmission τ_{T}	300 ms per data
	Propagation τ_{P}	500 ms per hop
	Caching (queuing) τ_{Q}	100 ms per data
	Calculation τ_{C}	1,000 ms per data

The AoI is a time-dependent metric; in other words, delays carry a significant weight. As shown in Figure 2(b), four delays are considered: transmission delay propagation delay, caching (queuing) delay, and calculation delay. Transmission delay, τ_{T}, occurs when the transmitter-side node generates data and converts it into packet, including packetizing (framing), both source and channel coding, and modulation over the air interface and via the network system. Propagation delay, τ_{P}, is the time interval for wireless transmission, which is primarily dominated by the distance between SN/SAN and RN/PBS, and radio-link conditions. Caching delay, τ_{Q}, occurs due to network congestion and significant queueing delays related to the network operations, such as routing, switching, and protocol processing. Calculation delay, τ_{C}, arises during computational calculations in the functors, depending on the hardware and software implementations.

As shown in Figure 2(b), let G_t denotes the generative function of the data in any k-th SN/SAN; therefore, the AoI is expressed as shown in Figure 2(c). Namely, for any k-th SN/SAN (i.e., the subscription of k is ignored for simplicity), let α_t and β_t denote the timestamp of the data generation and reception at t, respectively. Note that we can rewrite $G_t = \alpha_t - \alpha_{t-1}$. Letting $\ell(t) \triangleq \beta_t - \alpha_t$ denotes the freshness of the most recently updated data; hence, the AoI at the time t can be expressed as

$$\Delta(t) = t - \ell(t) \quad (2)$$

where $\ell(t)$ for the link between SN/SAN and RN can be rewritten on the basis of the previously defined latencies as

$$\ell(t) = \tau_{\mathrm{T}} + \tau_{\mathrm{P}} + \tau_{\mathrm{Q}} + \tau_{\mathrm{C}} \quad (3)$$

and for the wireless link between SN/SAN and PBS, i.e., under multi-hop conditions, $\ell(t)$ can be calculated multiplying (3) by the number of hops, but each delay depends on the individual nodes and wireless communication channels. In practical aspects, ℓ can be calculated from the timestamp recorded in the named data and the current time, under assuming the local time on the network nodes is synchronized.

IV. NUMERICAL RESULTS

This section provides a preliminary evaluation of the ICWSN/ICWSAN system with AoI based on the ICWSN platform [8] and the ICWSAN platform [14]. The computer simulations include ICN's cache functionality, functors, queues, and wireless communication. Figure 3 shows the simulation environment, and Table I listed the simulation parameters. As shown in Figure 3(a), the SNs were randomly deployed across a 1-km^2 field, and the RNs are placed in a rectangular lattice pattern. The wireless link between SN and RN was assumed to use microwave-band radio with single-hop transmission, and the links between RN and RN (or PBS) were assumed to use millimeter-wave (mmWave)-band radio with multi-hop transmissions. The number of wireless channels was determined based on Wireless Local Area

Networks (WLANs), i.e., IEEE 802.11 standard (see Table I). Namely, in microwave bands, such as 2.4/5-GHz WANs, the bandwidth per channel is 20 MHz and the number of channels is counted fully independent spectrum without overlapping. While, in mmWaves, IEEE 802.11 ad/ay-compliant WLANs is assumed, and it generally assigns four 2.16-GHz-bandwidth channels in the 60 GHz band. Therefore, the number of channels was calculated based on the spectrum allocated to the mmWaves, at the same channel bandwidth in the microWaves.

To simplify the simulations, the delay parameters were set to constant values, and further in-depth investigation remains a task for the future. Nemaly, the routing path for ICWSN and ICWSAN was predefined and fixed. The data, such as named data, packets, and frames, were assumed to be fixed in size. The source and channel coding method and the modulation and demodulation scheme were worked under the same conditions. The channel conditions remained stable (unchanged), i.e., no retransmissions occurred within the coverage area. The data processing for the individual data was performed under the same conditions, with the same computer performance on the network nodes. Furthermore, the size of cache memories (storage) on the network nodes was unlimited, i.e., the data was not lost due to overflow. Since the proposed AoI metric is significantly depending on the interval between the data generation and reception, the accurate clock synchronization across network nodes is essential for its correct operation. The paper assumes that time synchronization among nodes is consistently maintained; practically, a periodic time synchronization using GPS or Network Time Protocol (NTP) technique is feasible and required. In addition, this simplification may be acceptable for propagation, transmission, and computation delays, but it is problematic in the case of queuing delays. Therefore, the effect of the proposed metric in an actual network environment remains an ongoing consideration.

Figures 4–6 show the simulation results. Figure 4 shows the Cumulative Distribution Function (CDF) of the number of SNs accommodated in an RN. As a result, the number of SNs per RN was unbalanced, and the minimum was 117, the maximum was 718, the average was 400, and the median was 322, respectively. In practice, the distribution of SNs is also non-uniform, so the results are expected to be even more biased. Here, for simplicity, we assumed that an RN contains 400 SNs. Figure 5 shows the channel occupancy rate, average number of lost data, and average data size accumulated in the receiver-side buffer versus the interval between data generations (without interference) and the number of interference nodes (corresponding to one to four neighborhood RNs), as shown in Figure 3(b). Given a data generation interval of 30 s or longer and no interference nodes, the system can handle the data without packet loss or buffer overflow. Note that this simulation assumes an unlimited buffer capacity for simplicity, but in practice, buffers typically have upper limits, and the overflow can cause data loss. As shown in Figures 5(a) and (b), for generation intervals of 30 s and 60 s, even with an interference node present (up to four neighboring cells), the results showed that the system worked properly with a 60-s interval, whereas it was completely ineffective with a 30-s interval. As shown in Figure 5(c), the

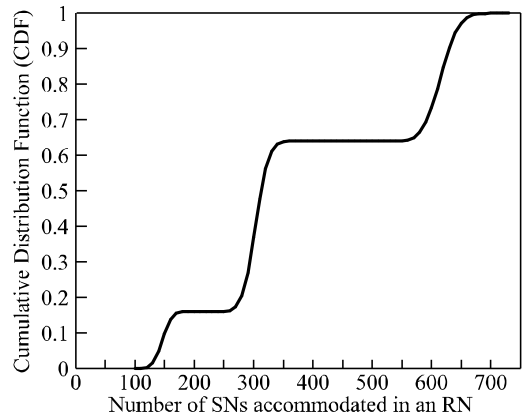

Figure 4. CDF versus number of SNs accommodated in RN

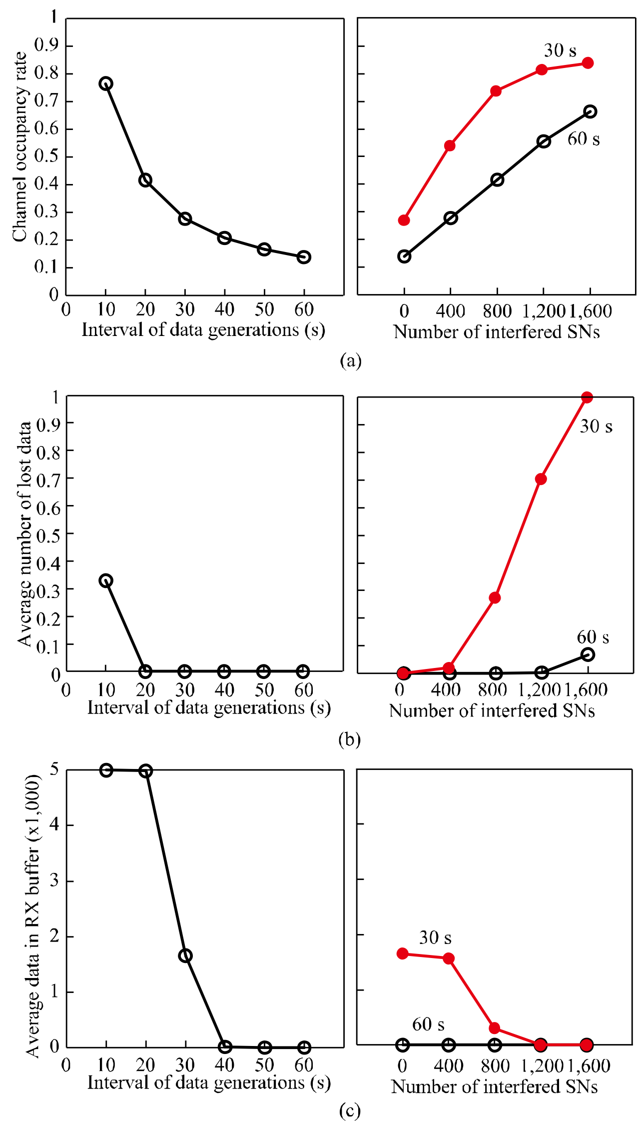

Figure 5. Channel occupancy rate, average number of lost data, and average data size accumulated in receiver-side buffer versus data-generation interval and number of interferenced nodes

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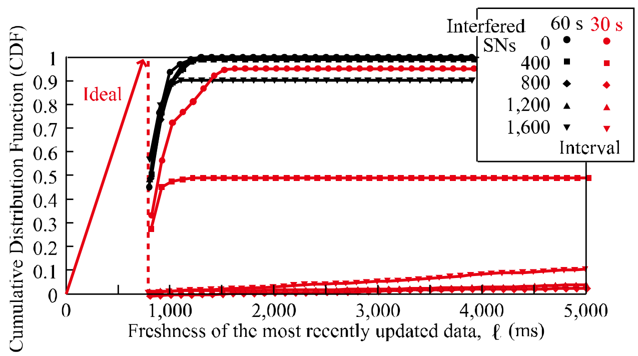

Figure 6. CDF versus freshness of most recently updated data

receive buffer is improved when the amount of generated data increases, i.e., the interval and interfered nodes were increased, because the buffer is overflowed and then the data cannot reach the receiver-side node.

Figure 6 shows the CDF versus the freshness of the most recently updated data, ℓ, as a numerical example directly related to AoI. Under ideal conditions, the delay would be 800 ms as represented by the arrow in the figure. However, due to the wireless channel, the receiver-side buffer, and interference from neighbor nodes, the arrival time (β) was delayed, resulting in a larger ℓ. For 60-s intervals, the data arrives within 1,500 ms, even with interference from neighbors. Based on these numerical results, the constant parameters should be determined to ensure that AoI-based data freshness is appropriately performed depending on the network scale, which is a future study and ongoing work.

V. Conclusion and Future Work

This paper proposed to introduce an AoI-based metric to the ICWSAN system as an essential delay indicator for delay-sensitive applications and provided a preliminary evaluation. As a future work, more detailed simulations and evaluations should be conducted.

Acknowledgments

This work was partly supported by JSPS KAKENHI Grant Number JP25K15104.

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Combining Multicast ABR and Information-Centric Networking

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***Abstract*— Live video streaming through the Internet is being widely used in the content distribution of popular concerts and bid sport events. There are several technologies to realize it, and among them, the multicast Adaptive BitRate (mABR) provides efficient network utilization accommodating a large number of clients. Actually, it is adopted by some network operators. It realizes the efficient content data transfer using IP multicast. However, mABR uses a unicast data transfer for the retransmissions of corrupted content data. This mechanism may introduce a situation that a large number of clients request the same content data at the same time. On the other hand, the Information-Centric Networking (ICN) is another technology to realize a multicast type content delivery by the content name data identification and the network caching. ICN is a pull-based architecture and some efforts are required to adapt it for the live video streaming. This paper proposes a new approach to combine the mABR and ICN architectures to realize efficient content delivery. Content data are delivered by use of mABR and corrupted data are retransmitted by use of ICN. The results of performance evaluation show that our proposal reduces the retransmitted data largely comparing with the original mABR.**

Keywords-Adaptive BitRae; Multicast ABR; Information-Centric Network; IP Multicast.

I. INTRODUCTION

Live video streaming through the Internet is being widely used for distributing various contents such as popular concerts and big sport events. There are several technologies to realize it. Most popular one is the MPEG-DASH (Moving Picture Experts Group-Dynamic Adaptive Streaming over HTTP) [1]. In MPEG-DASH, the content distribution is performed as a style of Web server access via a point-to-point connection. It allows clients to watch TV broadcasting using their web browsers, but the congestion in servers or networks may occur when a large number of clients request the same content. Actually, the FIFA World Cup Qatar 2022 was broadcasted with the MPEG-DASH technology by ABEMA in Japan, but some clients did not access the server by its congestion [2].

A way to provide efficient live video streaming is to introduce the multicast scheme. One approach is IPTV (Internet Protocol Television) [3], which introduces the IP multicast between client-side set-top boxes and headends, and requires that networks should be managed with QoS guarantees. The problems of IPTV are that it requires multicast support in access networks and that clients are not HTTP-based.

Another approach is the Information-Centric Networking (ICN). It is a new network architecture suited for a large scale content retrieval, and the Named-Data Networking (NDN) [4] is one of the representative studies. In NDN, content is identified by its name, not by the address of the host containing it. A consumer, a client, requesting a content sends an Interest packet containing the content name. A producer, a server providing the corresponding content data returns a Data packet to the consumer backward through the path that the Interest path traversed. Intermediate NDN routers transferring the Data packet cache the packet for future redistribution. However, NDN is a pull-based architecture, where a consumer requests an individual content segment explicitly, and so it does not fit a push-based data transfer in the real-time content delivery in live video streaming. There are some studies to adapt NDN to live streaming [5][6]. Both of them eliminate the one-to-one correspondent between Interest and Data packets, and introduce a long-lived Interest packet called a Symbolic Interest or a Persistent Interest. But in the current situation, ICN or NDN itself is still in the research stage.

The most realistic technology is the multicast Adaptive BitRate (mABR) [7], which extends MPEG-DASH by adopting an IP multicast in the delivery network. In mABR, the multicast server and the multicast gateway are introduced inside the network and they delivery content data using IP multicast. The communication between clients playbacking contents and the multicast gateways as well as that between the multicast servers and the content hosts are HTTP-based unicast and pull interactions. It can be said that mABR provides the standard HTTP ABR streaming and avoids the congestions in servers and networks. Actually, several network operators, such as Orange S.A. and Telecom Italy, offer live video delivery services using mABR [8][9]. In mMBR, however, corrupted content segments are retransmitted by unicast via the Unicast repair service, and so it may be possible that if data are corrupted in some link close to the multicast server, a lot of retransmission requests are sent to the unicast repair service and a lot of retransmitted data rush to the delivery network.

In order to resolve this problem, this paper proposes a new network architecture combining the mABR-based content delivery and the ICN-based content efficient segment retransmission.

The rest of this paper is organized as follows. Section 2 gives some background information including the overviews of mABR and ICN. Section 3 proposes our new network architecture combining mABR and ICN. Section 4 provides the results of performance evaluation focusing on the retransmission of corrupted content segments. In the end, Section 5 concludes this paper.

II. BACKGROUNDS ON MABR AND NDN

A. mABR

1) Overview

Figure 1 shows the overall architecture and the interfaces between modules in mABR. Video contents are stored in the *Content hosting* module, and the *Multicast server* requests and delivers them to the *Multicast gateway* and *Unicast repair service* modules. The *Content playback* module, which corresponds to a user terminal device, requests the delivered contents to the corresponding Multicast gateway storing the contents in the cache called *Asset storage*.

The interface between the Content playback and the Multicast gateway, *L*, is the HTTP-based unicast interaction, and so the conventional MPEG-DASH terminals can be uses as they are. On the other hand, the interface between the Multicast server and the Multicast gateways, *M*, is the IP multicast-based interaction. When some Content playback modules request a specific content or the delivery of the content is scheduled, the corresponding Multicast gateway requests its delivery by IGMP (Internet Group Management Protocol) or MLD (Multicast Listener Discovery). Then, the multicast delivery tree is established between the Multicast server and the Multicast gateway by use of the multicast routing protocol. The interface between the Content hosting module and the Multicast server, *Oin*, is again a pull-based unicast interaction, which is functionally identical to interface *L*. The push-type interaction, such as HTTP push method may be used in this interface.

The Unicast repair service module offers the payload repair function. Normally, the Unicast repair service module listens to multicast content transmissions over interface *M*, and caches the packets locally. When a Multicast gateway detects a loss or a corruption of some content segment, then it requests the retransmission of the segment to the Unicast repair service module through interface *U*. If the Unicast repair service module itself detects a corruption, then it requests the corrupted packet to the Multicast server through interface *U'*.

2) Application Layer for Multicast Delivery

Figure 2 shows the protocol stack in the Multicast server and Multicast gateway modules. Both of them have a dual

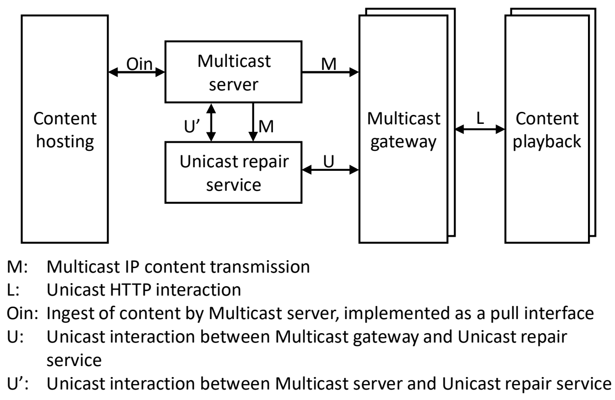

Figure 1. Overall architecture of mABR.

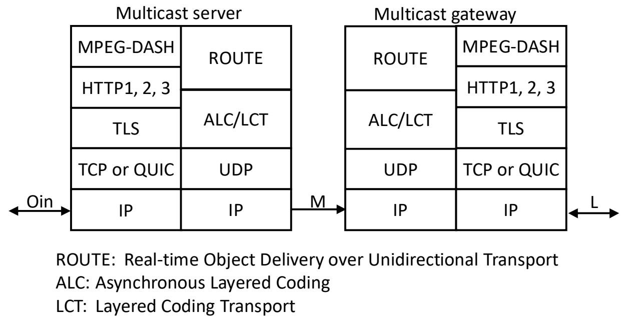

Figure 2. Protocol stack in Multicast server and Multicast gateway.

protocol stack structure, one stack for HTTP-based MPEG-DASH interactions and another for IP multicast-based content delivery. The HTTP-based protocol stack includes MPEG-DASH over HTTP stack, which uses HTTP/1, 2, or 3. For the case of HTTP/1 and 2, TCP is used as a transport layer, and for HTTP/3, QUIC and UDP are used as a transport.

For the side of multicast-based content delivery, mABR defines two protocols; File Delivery over Unidirectional Transport (FLUTE) [10] and Real-time Object Delivery over Unidirectional Transport (ROUTE) [11]. FLUTE handles an individual content segment as a separate file, and is well suited for non-real time delivery over lossy links. On the other hand, ROUTE is designed for the real-time media object delivery, particularly for broadcast/TV environments. Therefore, this paper uses ROUTE for the application layer in the delivery network.

As shown in Figure 2, the ROUTE protocol stack includes Asynchronous Layered Coding (ALC) [12] and Layered Coding Transport (LCT) [13]. ALC is a massively scalable reliable content delivery protocol for multiple rate congestion controlled content delivery, which is specifically designed for IP multicast as the underlying network service. It uses LCT as a header format of a ROUTE packet, which includes Transport Session Identifier (TSI) and Transport Object Identifier (TOI). TSI uniquely identifies a session among all sessions from a particular sender. TOI identifies a specific DASH segment.

It should be noted that the ROUTE protocol divides a content segment handled in the MPEG-DASH protocol into multiple ROUTE packets, whose size is smaller than MTU size used by the delivery network. So, the IP fragmentation does not happen during the IP multicast transmission. To identify a ROUTE packet explicitly, ROUTE packet header includes Payload ID, which shows the start_offsset specifying the number of the first octet in the contest segment carried in this packet.

It should be also noted that the URL used in the MPEG-DASH/HTTP protocol stack is not specified explicitly in the ROUTE protocol stack. The URL information is mapped to the TSI and TOI values in the LCT header.

The following is an example of relationship between the URL information and the TSI/TOI values. A Multicast gateway or a Multicast server module requests a specific content segment by its URL, in the form of

http://netoperatorA.net/live/channel1/3000k/segment_1000.m4s.
In this case, chanel1 corresponds to the multicast channel supported by this network operator and so the TSI value is assigned to a value of 0x1001. The sequence number assigned to the segment, a value of 1000, identifies the DASH segment, and so the TOI value also becomes 1000.

3) Unicast Repairng

On the other hand, the retransmission of lost or corrupted segments is performed by the unicast HTTP-based interactions between Multicast gateway and the Unicast repair service, or between the Unicast repair service and Multicast server. For example, when the Multicast gateway detects a packet loss, then it sends a HTTP GET request with Range request header specifying the lost data. An example is as follows supposing that data corresponding to byte 500 through 1900 are lost in segment segment_1000.m4s.

```
HTTP GET /live/channel1/3000k/segment
        _1000.m4s
Range: bytes=500-1900
Host: netoperatorA.net
```

B. NDN and its Application to Live Streaming

NDN nodes (consumers, NDN routers, and producers) maintain the following major data structures [4].

- Forwarding Information Base (FIB): used to forward Interest packets toward producers of matching Data.
- Pending Interest Table (PIT): keeps track of forwarded Interest packets for returning Data packets.
- Content Store (CS): caches received Data packets.

When an Interest packet arrives on some face, the content name in the Interest is looked up. If there is a copy of the corresponding Data packet in CS, it is sent out to the face the Interest packet arrived on and the Interest packet is discarded. Otherwise, if there is a PIT entry exactly matching to the received content name, the Interest's arrival face is added to the PIT entry and the Interest packet is discarded. Otherwise, if there is a matching FIB entry, then the Interest packet is sent to the face specified in the FIB entry.

By the help of these data structures, NDN provides a multicast-type content delivery. As described in Section 1, however, NDN is based on the pull-type communication, requires an Interest packet transfer for each content segment.

Two references [5][6] proposed a similar way to avoid the overhead of frequent Interest packets. In [5], a new type of Interest, Symbolic Interest, is proposed. A Symbolic Interest includes the content name and the duration, but does not require the sequence number specific to individual segment to be specified. When an NDN router receives a Symbolic Interest, it expands the life time of PIT entry for the specified duration, and keeps the corresponding Data packets to be delivered during the duration.

III. COMBINATION OF MABR AND ICN

A. Overviews

We adopted the following design principles to coordinate mABR and ICN.

(1) Use NDN as a tool to retransmit a lost or corrupted content segment instead the unicast repair mechanism in the current mABR. The multicast-based content delivery within the delivery network is used as it is.

(2) Some NDN nodes called NDN proxies are implemented within the delivery network. They work as IP multicast receivers similarly with the Multicast gateway nodes. They handle received ROUTE packets as NDN Data packets and store in its Content Store. The Multicast server also works as an NDN producer, and the Multicast gateways work as NDN consumers. This means that NDN Interest/Data packet exchanges are not performed in the initial delivery of content segments. Instead, the IP multicast is used in the initial delivery.

(3) When a Multicast gateway detects the loss or the corruption of a ROUTE packet, it requests this packet via the NDN interaction. That is, the Multicast gateway sends an Interest packet requesting the ROUTE packet to the corresponding NDN proxy. If the NDN proxy has the ROUTE packet in its CS, it returns the corresponding Data packet. If not, the NDN proxy consults its PIT for this Interest, and sends the Interest packet to the upstream NDN proxy or the Multicast server (the producer), if the PIT does not maintain the entry corresponding to the Interest packet.

(4) The content name specifying a ROUTE packet is composed using the corresponding TSI, TOI, and Payload ID values of the ROUTE packet.

(5) The NDN level network is constructed with the help of NDN routing protocol, such as NLSR [14]. Interest and Data packets are transferred using TCP for the reliable transfer [15].

B. Network Configuration and Protocol Stack

Figure 3 illustrates the proposed network configuration. The delivery network consists of IP routers supporting IP multicast. The Multicast server / NDN producer and the Multicast gateways / NDN consumers are connected to the delivery network. Multiple NDN proxies are installed within the delivery network. They are connected with a nearby IP router.

A multicast tree is constructed with the Multicast server being the root of the tree. The Multicast gateways and the NDN proxies work as the leaves of the tree. The relationship of NDN producer, routers, and consumers are established among the Multicast server, NDN proxies, and Multicast gateways, as shown in the figure.

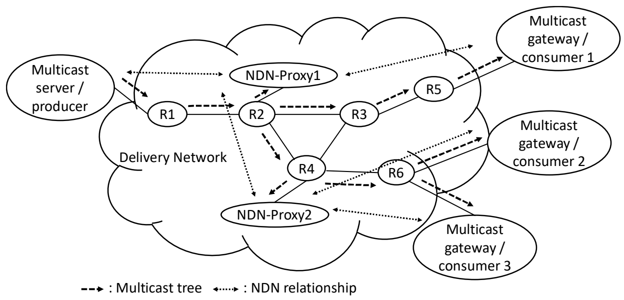

Figure 3. Proposed network configuration.

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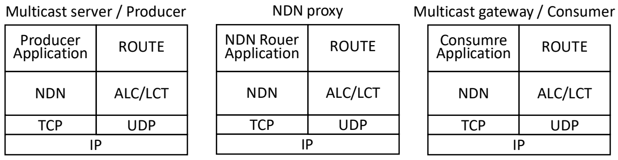


Figure 4. Protocol stack used in delivery network.

Figure 4 shows the protocol stack of the nodes used in the delivery network. All of them include the protocol stacks for the ROUTE multicast content delivery and the NDN content delivery. As mentioned above, ROUTE uses UDP and in this paper NDN uses TCP as a transport protocol.

C. Mapping among DASH URL, ROUTE Packet Header, and NDN Content Name

As described in the previous section, the content to be delivered is identified by some URL which identifies an MPEG content segment. It takes a style of

http://<domain-name-of-multicast-server>/<service-name>/<segment-identifier>.

In the example given above. <domain-name-of-multicast-server> is `netoperatorA.net`, <service-name> is `live/channel1/3000k`, and <segment-identifier> is `segment_1000.m4s`. This URL information can be constructed from the information stored in the MPD (Media Presentation Description) file of the content.

The parameter values of ROUTE packet header, TSI, TOI, and Payload ID, are derived from the URL information. The value of TSI identifying the session corresponds to the part of <service-name> in the URL. The value of TOI specifying a specific object in the session corresponds to the part of <segment-identifier> in the URL. In the previous example, the value of TSI is set to `0x1001`, and the value of TOI is set to `1000` by number part of the segment ID `segment_1000.m4s`. In the ROUTE protocol, the segment is fragmented into ROUTE packets in the application layer. Each packet is identified by Payload ID specifying the offset of the first octet contained in the packet. The Payload ID of the first ROUTE packet carrying a content segment will be `1`, and that of the second ROUTE packet will be `1401`, when the MTU size is 1,400 bytes.

The IP multicast address used in the delivery network is defined according to the policy of the network operator managing the delivery network. The multicast address needs to be unique within the delivery network, and does not need to be unique globally. So, a possibility is to use the source-specific multicast range (232.0.0.0/8). The multicast address for a specific Multicast server and for a specific live content can be determined according to the policy of the delivery network.

In the proposed method, the NDN system in the delivery network handles ROUTE packets as individual content segments. Therefore, the content name in our proposal will be specified by the combination of the Multicast server ID, the multicast flow ID (TSI), the object ID specifying the segment conveyed in the flow (TOI), and the ID of the fragmentation of the fragment conveyed in the ROUTE packet. So, the content name specifying a ROUTE packet can be a style of

/<domain-name-of-multicast-server>/<TSI>/<TOI >/<start_offset>.

The example will be

`/netoperatorA.net/0x0001/1000/1`.

D. Sequence Example of Retransmission

Figure 5 shows an example of communication sequence in our proposal. In the beginning, the Multicast server requests a content segment whose URL is `http://A/live/seg1000`. When the Content hosting returns the data of this segment, the Multicast server starts the delivery. In this figure, we suppose that the content segment is divided into ten ROUTE packets each of which has 1,400-byte data. They are delivered by IP multicast to NDN proxy and Multicast gateway. In the NDN proxy, individual ROUTE packets are stored as Data packet in its content cache. In the Multicast gateway, the content segment is reconstructed and stored in its Asset storage. The Content playback will request this segment via HTTP interaction.

In the delivery of the second content segment, the figure shows two cases of transmission error and its recovery. In the first case, the ROUTE packet containing bytes 1401:2800 is lost before the Multicast gateway receives it. Then the gateway sends an NDN Interest packet with content name `/A/0x1000/1001/1401`. Since the corresponding data is cached in the NDN proxy, the proxy returns the corresponding Data packet immediately.

In the second case, the sixth ROUTE packet containing bytes `7001:8400` is lost and none of the NDN proxy nor the gateway receive it. In this case, the gateway sends an Interest packet with content name `/A/0x1000/1001/7001`. Since the NDN proxy does not have the corresponding data, it relays the Interest packet to the Multicast server / producer. The producer returns the corresponding Data packet to the proxy, and the proxy relays the Data packet to the Multicast gateway.

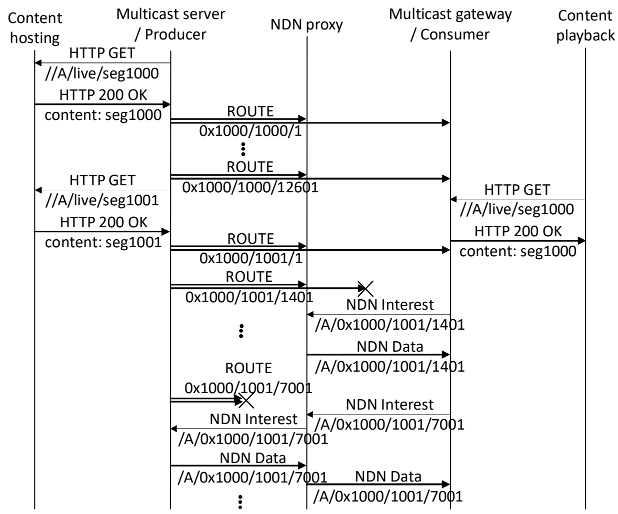


Figure 5. Example of communication sequence.

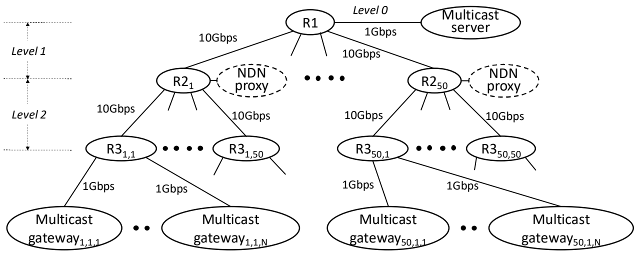


Figure 6. Network structure for evaluation.

It should be noted that, even if there are multiple Multicast gateway, only one Interest packet will be relayed to the Multicast server, because the Interest is specified in the PIT or the received Data packet is cached in the proxy.

IV. PERFORMANCE EVALUATION

A. Conditions for Evaluation

Figure 6 shows the network structure used for the performance evaluation. This configuration is a hierarchical style which is designed by supposing the network in Japan. Router *R1* is the root router to which the Multicast server is connected. Routers $R2_1$ through $R2_{50}$ are intermediate routers, which are installed in the prefecture level. Routers $R3_{i,1}$ through $R3_{i,50}$ are access routers located below router $R2_i$ (i=1 to 50). Under access routers, N Multicast gateways are accommodated. The transmission rate of individual links is specified in the figure. In the proposed method, the NDN proxies are connected to the intermediate routers. We suppose that the one-way delays between the Multicast server and individual Multicast gateways take random values between 10 msec and 50 msec.

As a content delivered over this network, we assume the full HD video, whose bitrate is 5 Mbps. The ROUTE packet size is 1,400 bytes, and so the packet rate is 0.446 K packets per sec (pps).

We assume the packet losses in links of individual levels; level 0 through level 2 as depicted in the figure. The packet loss rate is denoted by p, which contains the losses in the link and the router. We approximate those losses as random errors.

In the original mABR, when a packet loss occurs, the Multicast gateways request the lost packet to the Unicast repair service module installed in the Multicast server. This request is done by the HTTP communication, and so the Multicast gateway establishes a TCP connection with the Multicast server in the beginning. After that, the individual Multicast gateway sends an HTTP GET command, as described in Subsection 2.A.3), to request the content data corresponding to the lost ROUTE packet. Since the ROUTE packets are delivered to all the requesting Multicast gateways, the retransmission requests are performed by multiple gateways in a short time frame. That is, the TCP SYN packets and the HTTP GET commands rush into the Multicast server. These communication sequences will provide the Multicast server with two types of heavy loads. One is a traffic congestion like a TCP SYN floods DDoS attack. Another is a heavy traffic load of the HTTP GET responses conveying the lost data sent by the Multicast server. We evaluate these two traffic loads as for the original mABR.

In the proposed method, when a packet loss occurs, the Multicast gateways send an Interest packet for the lost packet to the corresponding NDN proxies. If the NDN proxy sores the lost packet in its Content Store, it returns the lost packet by the NDN Data packet, else the Interest packet is forwarded to the Multicast server when it is the first request. In those cases, a TCP connection is established to the NDN proxy or to the Multicast server. So, we evaluate the following two aspects: the TCP SYN congestion at Multicast server and at NDN proxy and the traffic load of Data packets sent by the NDN proxies and the Multicast server.

B. Evaluation of TCP SYN Congestion

The TCP SYN congestion is evaluated by focusing on one ROUTE packet loss. When a ROUTE packet is lost in the level 0 link, all of the Multicast gateways do not receive the packet, and try to request the retransmission. In the original mABR, all of the Multicast gateways establish TCP connections to the Multicast server. The number of the transmitted TCP SYN segments is $N \times 50 \times 50 = 2500 \cdot N$. Since the round-trip delay between the Multicast server and the individual Multicast gateway takes a value between 20 msec and 100 msec, these SYN segments rush to the Multicast server during 80 msec. So, the rate of SYN segments is $2500 \cdot N / 0.08 = 31250 \cdot N$ pps.

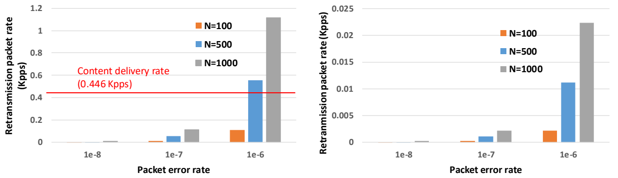
In the proposed method, a Multicast gateway establishes a TCP connection to the corresponding NDN proxy in order to send an Interest packet. The number of the SYN segments transmitted to one NDN proxy is $N \times 50 = 50 \cdot N$. The rate of SYN segments is $625 \cdot N$ pps. Each NDN proxy establishes a TCP connection to the Multicast server, and so the number of TCP SYN segments is 50 and the rate is 625 pps.

We use 100, 500, and 1,000 as the value of N. It is reported that the number of access to the FIFA World Cup Qatar 2022 content delivery exceeded 23 million [16], which is the result of access throughout one football match. The case of N = 1,000 corresponds to 2.5 million simultaneous access, which may be comparable with the 23 million access in one content.

Table I shows the TCP SYN segment rate caused by one ROUTE packet loss. In the original mABR, the case of N = 1,000 provides 31.25 Mpps SYN segments. This is almost a level of SYN flood DDoS attack. A DDoS attack example Google server suffered in 2020 is reported as 167 Mpps [17]. Moreover, if the SYN segment size is 50 bytes, the total SYN traffic in the case of N = 1,000 becomes 12.5 Gbps. This traffic cannot be transferred through the 1 Gbps link between *R0* and the Multicast server. This also says that the SYN rate

TABLE I. TCP SYN SEGMENT RATE FOR ONE ROUTE PACKET LOSS

		N=100	N=500	N=1000
original mABR	to Multicast server	3.125 Mpps	15.625 Mpps	31.25 Mpps
proposed	to NDN proxy	62.5 Kpps	312.5 Kpps	625 Kpps
	to Multicast server	625 pps	625 pps	625 pps



(a) Retransmission from Multicast server in original mABR

(b) Retransmission from an NDN proxy in proposed method

Figure 7. Retransmission packet rate.

in the original mABR is extremely heavy. On the other hand, the proposed method can lighten the SYN segment congestion as shown in the table.

C. *Evaluation of Retransmitted Traffic Load*

The next evaluation point is the traffic load of retransmitted packets from the Multicast server or the NDN proxies. As mentioned above, we assume the packet loss rate is p for individual links. For the packet losses in the Level 0 link, the expected value of retransmission packet rate in the original mABR will be *the multicast packet rate* $\times$ p $\times$ 2500 $\times N$. When packet losses occur at some link in the Level 1, the expected value in the original mABR will be *the multicast packet rate* $\times 50 \times$ p $\times$ $50 \times N$. This is the same result as the case in the packet losses in the Level 0. Therefore, we assume that packet losses occur at the link between *R0* and Multicast server in Figure 6.

We assume that the coding rate of the content is 5 Mbps, that is 0.446 Kpps when a ROUTE packet includes 1,400-byte content data. So, in the original mABR, the retransmission packet rate from the Multicast server is $0.446 \times 2500 \times p \times N = 1115 \cdot p \cdot N$ (Kpps). On the other hand, in the proposed method, the retransmission packet rate from the individual NDN proxy is $0.446 \times 50 \times p \times N = 22.3 \cdot p \cdot N$ (Kpps), and the retransmission packet rate from the Multicast server to the individual NDN proxy is $0.446 \times 50 \times p = 22.3 \cdot p$ (Kpps).

Figure 7 shows the results for $p = 10^{-8}$, 10^{-7} and 10^{-6}, and N = 100, 500 and 1,000. In the original mABR, the retransmission packet rate from the Multicast server is relatively large. Especially when the packet loss rate is 10^{-6}, the retransmission packet rate is larger than the content delivery rate in the cases of $N = 500$ and $N = 1{,}000$. In contrast, the retransmission packet rate from one NDN proxy is much smaller than the result in the original mABR. This shows the effectiveness of our proposal.

V. Conclusion and Future Work

In this paper, we proposed a scheme to combine the multicast ABR and the information-centric networking, specifically the named data networking. mABR is actually adopted by some network operators and is used for the efficient live content delivery by making Multicast server transfer content packets via IP multicast. However, when some multicast packets are lost or corrupted, the retransmission of those packets are performed by the unicast repair communication. This mechanism may introduce a heavy congestion when a large number of clients, Multicast gateways, request retransmissions for a specific content packet. This paper proposed an approach that the retransmission is performed by the NDN scheme. Several NDN proxies are introduced in the delivery network, and they behave as a multicast client in ordinary times receiving content packets and storing them in their content stores. When some Multicast gateways detect packet losses, they request the lost packets to the corresponding NDN proxies. The results of the performance evaluation confirmed that the proposed method provide an efficiency in terms of the TCP SYN sending and the retransmitted traffic load. As a future work, we will design the similar scheme using HTTP proxy.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number JP25K15075.

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