Recovering Content Availability at Failures in ICN

Noriaki Kamiyama
Fukuoka University, Fukuoka, 814-0180 Japan
E-mail: kamiyama@fukuoka-u.ac.jp

***Abstract*—To be widely spread as a social infrastructure, ICN (information-centric networking) is required to sustain not only *network availability*, i.e., connectivity between operating routers, but also *content availability*, i.e., reachability to content, at network failures. In ICN, FIBs (forwarding information bases) at routers are configured so that content requests reach hosts of content providers having the originals of content. Hence, requests for content whose connectivity to originals is lost cannot be transferred in networks, and the content availability of these content items is lost. However, copies of unavailable content are possibly cached at one or more operating routers in ICN. Therefore, in this paper, we propose to recover content availability by promoting one copy cached at operating routers to the original and updating FIBs so that content requests are transferred to the newly-promoted original. We also propose a method of selecting one copy so that the minimum average distance to other operating routers is minimized when copies are cached at multiple operating routers. Through numerical evaluation, we show that the availability of about 5% to 20% unavailable content items are recovered by the proposed method.**

I. Introduction

Traffic generated by delivering content including web, user generated content (UGC), e.g., YouTube, and rich content produced by content providers, e.g., movie and dramas, has dominated more than 90% of traffic in the Internet [6]. In the Internet, packets are routed by using IP addresses as locators, so the overhead for resolving the IP addresses of destination hosts from the content names is indispensable. Therefore, as a new network architecture efficiently delivering content without this overhead, information-centric networking (ICN), which caches content at routers and forwards packets using the content name, has attracted wide attention [9]. Using ICN, we can avoid the overhead of resolving the IP addresses and expect to reduce the delay and network load by delivering content from nearby location to users. To realize the idea of ICN, various networks, such as TRIAD [13], content-centric networking (CCN) [15], data-oriented network architecture (DONA) [17], and named data networking (NDN) [33], have been proposed [32]. Based on approaches locating the source of content, ICN architectures can be classified into two types: centralized *lookup-by-name* approach, e.g., PSIRP/PURSUIT [11], and *route-by-name* approach, e.g., CCN [15] and NDN [33]. In the former approach, a centralized name resolution server manages the location of content originals and resolves the source location for all requests. In the latter approach, requests are transferred to originals using the content name as locators.

Because of various reasons, such as disasters, cyberattacks, and human errors, we cannot avoid the risk of failures on routers and links in networks. In this paper, we define *operating routers* as routers which still normally operate without being affected by network failures. In order for ICN to be widely used as a social infrastructure, ICN is required to maintain high robustness at network failures so that users accommodated at operating routers can continue to obtain content. To achieve this goal, ICN needs to sustain *network availability*, i.e., connectivity between any pairs of operating routers. In addition to network availability, ICN is also required to sustain *content availability*, i.e., reachability to content from any operating routers. In this paper, we define *unavailable content* as content whose availability is lost at network failures. In the Internet transferring packets based on IP addresses, the network availability is recovered at network failures by reconstructing routes of packets through route advertisements of OSPF (Open Shortest Path First). To recover the network availability at network failures in ICN, Hoque et al. proposed NLSR (Named-data Link State Routing) which is an extension of the OSPF to support name-based routing and reconstruct routes of Interests by route advertisements of NLSR at network failures [14]. Therefore, using the similar approach with the Internet, the network availability can be recovered in ICN as well.

In the Internet, the content availability is sustained because CDN (Content Delivery Network) providers prepare and manage backup or mirror servers at various locations and deliver content from backup servers at network failures. In the ICN of look-by-name approach, content availability can be also sustained by providing mirror servers and selecting available originals by the name resolution server [3]. In the ICN of route-by-name approach, on the other hand, content providers called *Publishers* register their content items to networks, and content originals exist at hosts of Publishers. FIBs (forwarding information bases) at routers are configured so that content requests called *Interests* of users, i.e., *Subscribers*, are transferred to content originals stored at hosts of Publishers [32]. Therefore, if content originals are accommodated at routers whose connectivity is lost, routers cannot forward Interests for these content items, and the availability of these content items is lost.

A simple way to improve the robustness against the availability loss of content is providing multiple originals, i.e., mirrors, in the network for each content. However, if multiple originals exist in the network, routers need to select one original among multiple candidates for each Interest, so the computational overhead in forwarding Interests at routers increases. Moreover, providing multiple originals at various locations in the network will violate the hierarchical structure of name space [2], so the number of entries of FIBs increases as the number of originals increases. To simplify the routing and forwarding functions of routers, it is desirable to provide just a single original in the network. In ICN, copies of unavailable content could be possibly cached at some operating routers at the time of network failures. Therefore, for each unavailable content, we propose to promote one of copies existed at operating routers to the original and update the FIBs of operating routers so that Interests are transferred to the copy promoted to the original in the ICN of route-by-name

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approach. The contribution of this manuscript is summarized as follows.

- We newly propose to utilize copies cached at operating routers to recover the content availability at network failures in the ICN of route-by-name approach. The proposed method can recover the content availability without preparing mirrors of originals.
- When copies of unavailable content are cached at multiple operating routers, we need to select the location for promoting the copy to original, and it is desirable to reduce the hop length of delivery flows to reduce the amount of traffic in the networks. Therefore, we propose that one operating router collects the information of content cached at each operating router and the connectivity status, and it selects one copy from which the average hop length to other operating routers is minimal as the copy promoted to the original.
- Through computer simulations using the topologies of commercial ISP networks in USA, we investigate the effectiveness of the proposed method. We confirm that the proposed method recovers the availability of about 5% to 20% unavailable content, when each router has a cache memory with the capacity of 1% of the total content, and the availability of about 15% content is lost at network failure, for example.

II. Related Works

To improve the robustness against network failures, copies of each content should be cached at dispersed locations, and several authors proposed caching strategies to achieve this goal. For example, to explicitly avoiding duplicated caching in nearby areas, Rezazad et al. proposed limiting the cache positions on the default path to one router [26]. In other words, parts close to the head of the content are cached at only routers close to the user router, whereas parts close to the tail of the content are cached at only routers close to the source router. Moreover, Saino et al. [28] and Saha et al. [27] proposed assigning the range of hash values of content names without overlap to routers and caching content only at routers whose assigned range includes the hash value of the target content. Kamiyama, et al. also proposed a method of dispersing the cached location with hash values assigned to routers and differentiating the copy counts based on the content popularity [16]. However, all these methods did not consider recovering the content availability at network failures.

Mansour et al. proposed a Name-Centric Monitoring Protocol (NCMP) which enables a controller to discover failed copies at routers by sending an Interest packet to all routers to inquire the availability information of copies [21]. However, methods of recovering the content availability was not investigated. To recover the content availability at network failures in PSIRP/PURSUIT, Al-Naday et al. proposed to switch the sources of content deliveries to originals of other Publishers providing the same content [1]. However, this method cannot be applied to the ICN of route-by-name approach. Moreover, Sourlas et al. proposed to recover the content availability by utilizing user hosts obtaining the unavailable content as origin hosts [29]. However, routers need to implement tables to transfer Interests to user hosts, and user cooperation is necessary in this approach.

III. ICN and NLSR

A. Function of ICN Router

In this paper, we assume the network architecture of CCN and NDN as the ICN of route-by-name approach [15][33]. Users send Interests toward the origin servers, i.e., hosts of Publishers storing originals of content, and routers forward the Interests using the name of content. Like the OSPF, routers configure FIBs by calculating the minimum-cost routes, and routers determine the faces to which Interests are transferred by looking up the FIB [14][15]. FIB entries are looked up based on the content name instead of IP addresses, and the route of Interests is called *default path*. At each router, cache memory called *content store* (CS) is implemented to cache content[1], and a router on the default path sends the requested content to the user without forwarding the Interest to the next-hop router when the requested content is cached in the CS of the router. A table called PIT (Pending Interest Table) is also implemented at routers, and the PIT stores the face number where an Interest arrives. By looking up the PITs, routers forward the content to the next-hop router on the default path in the reverse direction, and the entries of PITs are removed when content are forwarded. Routers on the default path can cache content received.

B. Updating FIBs by NLSR

As a protocol to exchange various information between routers, we assume to use the functions of NLSR, i.e., updating FIBs and checking the availability of adjacent routers [14]. By periodically exchanging control packet called hello message with adjacent routers, IP routers confirm the availability of adjacent routers, recognize the entire topology of network, and set the FIBs [12]. In ICN, Interests are transferred using content name, so names are assigned to routers to exchange control packets between adjacent routers [14]. Like OSPF, routers update FIBs by using the Adjacency LSA (Link State Advertisement) exchanging the topology information with adjacent routers as well as the Prefix LSA exchanging the information of FIB entries in NLSR.

C. Extended Function of ICN Router

In this paper, we assume two extended functions of ICN routers in addition to the functions described in Section III-A: (i) measuring the number of observed Interests and (ii) perpetuating the lifetime of cached content. We assume that these two functions are executed at all routers at any time before and after network failures occur. Router n increments y_n, the counter of observed Interests, whenever receiving an Interest of any content from users accommodated at router n. Now, let us consider a time slot with a fixed length of T_m. At the boundary of time slots, router n sets Y_n, the number of Interests observed within the latest time slot, to y_n and initializes y_n to zero. As a result, router n records the number of Interests generated in the latest time slot in Y_n.

Routers need to perpetually store cached copies promoted to originals because Interests are transferred to these copies. However, content items cached in CS could be possibly removed from CS by cache-replacement method. To perpetually hold copies of content promoted to originals, we can consider two approaches: (i) providing extra memory to perpetually store copies promoted to originals besides CS and (ii) giving each cached content m a perpetual flag f_m indicating whether it can be removed or not without providing new memory. In the second approach, cached content items with $f_m = 0$ could be removed by cache-replacement policy, whereas those with $f_m = 1$ are never removed and perpetually stored in CS. Although the implementation cost of the second approach is

[1]Although content is divided into multiple chunks and is cached in the unit of chunks, we describe the unit of caching as content for simplicity.

smaller than that of the first approach, the storage capacity of CS in the second approach decreases because a part of CS is used for content promoted to originals. In the first approach, memory with slow access speed, e.g., DRAM, can be used to store originals because the promoted originals locate at the end point of application layer and can be sent at any bitrate. Therefore, low-cost memory can be used for storing the promoted originals, so the cost of additional memory will not become a problem even in the first approach.

IV. Method Recovering Content Availability

In this section, we describe the detail of the proposed method, called *CPO (Centralized Promotion for Original)*, recovering content availability. We assume to promote just a *single* copy to the original for each unavailable content by the *centralized* approach, i.e., one router called the IR (initiation router) selects the copies promoted to originals for all the unavailable content. In this case, the IR needs to wait the completion of FIB-update process before starting the promotion process if the Interests to collect the cached-content information are transferred using FIBs. To enable the IR to start the promotion process immediately after the failure detection, we propose to transfer the Interests inquiring the cached-content information by flooding them at routers without using FIBs. When the network is divided into multiple disconnected parts in large-scale failures, one router acts as the IR in each network part so that the content availability is recovered in each network part.

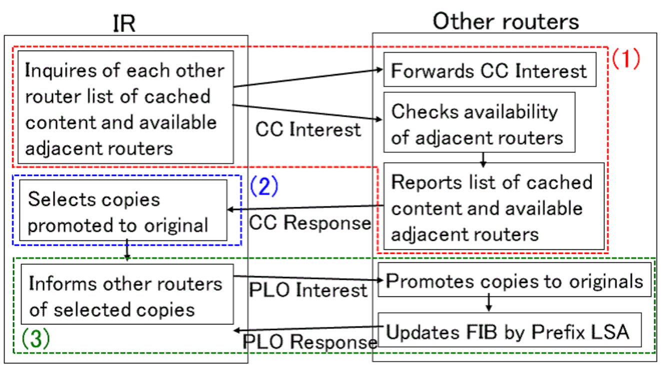

Fig. 1. Procedure of CPO

As shown in Fig. 1, the procedure of CPO consists of the three sub-processes: (1) state recognition by IR, (2) selection of promoted copies by IR, and (3) promotion process. We describe the detail of each sub-process in the following sub-sections.

A. State Recognition by IR

A router which detects failures on its adjacent routers or connected links by Adjacency LSA becomes the IR and determines the locations of new originals by selecting the copies promoted to the originals for all the unavailable content. To accomplish this goal, the IR initially needs to collect the information of unavailable content and the cached content at each operating router. When there are multiple operating routers adjacent to failed routers or links, multiple operating routers might become the IRs. If multiple IRs independently determine the locations of copies promoted to originals, different sets of copies might be selected by each IR, and multiple copies might be promoted to originals for the same unavailable content. Therefore, we need to implement a mechanism to limit the router becoming the IR to just a single operating router, and we describe the method to achieve this in Section IV-D.

We define $\boldsymbol{R}_a$ as the set of routers which the IR *can* reach, and we also define $\boldsymbol{R}_f$ as the set of routers which the IR *cannot* reach by using any routes due to network failure. Moreover, let $\boldsymbol{M}_f$ denote the set of content whose originals are provided at routers of $\boldsymbol{R}_f$. Letting $\boldsymbol{R}$ denote the set of all routers, we have $\boldsymbol{R}_f \cap \boldsymbol{R}_a = \phi$ and $\boldsymbol{R}_f \cup \boldsymbol{R}_a = \boldsymbol{R}$. Although the IR needs to know $\boldsymbol{R}_f$ to grasp $\boldsymbol{M}_f$, the IR can detect the failures at only its adjacent routers and its connected links. Moreover, the IR needs to know the content cached at routers of $\boldsymbol{R}_a$ to select copies promoted to originals. Therefore, the IR collects the information of $\boldsymbol{M}_f$ and the list of content cached at each router of $\boldsymbol{R}_a$ by sending the connectivity confirmation (CC) Interest to each of all other routers. This process consists of the three subprocesses: (i) sending CC Interest by IR, (ii) forwarding CC Interest by other routers, and (iii) returning CC Response by other routers.

(i) Sending CC Interest by IR
A router detecting loss of connectivity with its adjacent routers becomes the IR and immediately sends the CC Interest to all routers of $\boldsymbol{R}$ excluding itself. If the CC Interest is transferred using the FIBs, the CC Interest might not be able to reach some routers because of the link or router failure. Therefore, we assume that routers receiving the CC Interest forward it by *exploration*, i.e., broadcasting it to all the faces [10][31]. In [10][31], the authors proposed the exploration forwarding to improve the efficiency of content forwarding to a specific destination by expanding the candidate routes of Interests from the default path. However, the Interest arrives at all routers with connectivity when routers broadcast the Interest. Therefore, with the exploration forwarding without using the FIBs, the CC Interest will arrive at all routers with connectivity from the IR. The IR sends the CC Interest with the destination name set to the identification name of CC Interest and with the timestamp set to the current time. The timestamp is used to avoid the duplicated-IR problem, i.e., multiple IRs select copies promoted to originals, and the detail of timestamp function is described in Section IV-D.

(ii) Forwarding CC Interest by routers
Router n receiving the CC Interest drops it if its entry exists in its PIT because router n has already forwarded the CC Interest. Otherwise, router n executes the two processes: (a) creating a new PIT entry including the name of source router sending the CC Interest, i.e., the IR, and the face number A at which the CC Interest arrived, and (b) forwarding the CC Interest to all the faces excluding A. As a result, routers can avoid sending the same CC Interest two or more times, and routing loop of CC Interest is avoided. Let E_a denote the number of links which the IR can reach, and the CC Interest will arrive at all the routers of $\boldsymbol{R}_a$ from the IR within the total forwarding count E_a. We also note that transmission of CC Interests on each link is limited to just one time, so network congestion caused by CC Interests is avoided.

(iii) Returning CC Response by routers
Router n receiving the CC Interest checks the connectivity with each of its adjacent routers by the Adjacency LSA. Next, router n returns the IR the CC Response which includes the name list of all the content cached at router n, the name list of adjacent routers with connectivity, and Y_n, the number of Interests generated in the latest time slot. Router n' receiving the CC Response forwards it to the faces registered in the PIT

of router n' [15][33]. The PIT entry is removed when the data chunk is transferred in ICN. However, the PIT entry created by the CC Interest is used for multiple CC Reponses sent from different routers because the CC Interest is sent to all the routers of $\boldsymbol{R}_a$, so routers cannot remove the PIT entry when the CC Response firstly arrives at the routers. Therefore, router n' removes the PIT entry when a fixed period T_P elapses after the CC Response firstly arrives at router n'. The propagation delay on links is much smaller than D_A, the maximum time required to check the availability of adjacent routers. In the case of OSPF, a router can detect the loss of connectivity with adjacent routers by about two seconds at maximum [12]. Therefore, we can also estimate $D_A = 2$ seconds by using the NLSR, and we can set T_P to about two to three seconds including a margin.

Interests are still generated by users, and content items are still delivered to users during the process of the CPO. To avoid the inconsistency between content items actually cached at CSs and the name list of content reported to the IR, we assume that content items stored at CSs at routers are not changed, i.e., no content items are inserted to CSs, and no content items are evicted from CSs, after routers send the CC Response to the IR until the completion of the promotion process described in Section IV-C.

B. Selection of Promoted Copies by IR

The IR regards routers from which the CC Responses are not received within time period T_C as routers losing the connectivity from the IR. We can bound the upper limit of T_C by $(\delta_L + \delta_I + \delta_R)E + D_A$, where E is the number of links in the network, δ_L is the maximum propagation delay of links, and δ_I and δ_R is the maximum time required to send the CC Interest and the CC Response at routers, respectively. For example, when $E = 100$, $\delta_L = 5$ milliseconds, i.e., the maximum link length of 1,000 km, δ_I and δ_R are several hundred microseconds [30], and $D_A = 2$ seconds, we can set T_C to about three seconds.

Each router grasps the routers which accommodate hosts providing original of each content by the Prefix LSA before the network failure occurs. Therefore, by receiving the CC Responses from all the routers of $\boldsymbol{R}_a$, the IR can grasp $\boldsymbol{M}_f$, the set of unavailable content items, and the list of content cached at each router of $\boldsymbol{R}_a$. We define $\boldsymbol{C}_m$ as the set of routers caching copies of content m among $\boldsymbol{R}_a$. If just a single router is included in $\boldsymbol{C}_m$ for content m of $\boldsymbol{M}_f$, the copy of content m cached at this router is definitely selected to the copy promoted to the original of m. However, if multiple routers are included in $\boldsymbol{C}_m$, the IR needs to select one router among them as the copy promoted to the original.

Interests are transferred to the hosts providing the originals, so the selection of copies promoted to originals affects various network qualities, e.g., the length of delivery flows, the link load, and router load, after recovering the content availability. In this paper, we propose to select copies promoted to originals with minimizing the average hop length of delivery flows after recovering the content availability. Let x_m denote the router whose caching copy of content m of $\boldsymbol{M}_f$ is selected to be promoted to the original of m, and x_m is selected by

$$x_m = \arg \min_{x \in \boldsymbol{C}_m} \sum_{n \in \boldsymbol{R}_a} h_{n,x} r_n \qquad (1)$$

so that the average minimum hop length between users and the newly promoted original of content m is minimized. $h_{n,x}$ is the minimum hop length from router n to router x, and $h_{n,x}$ is derived by Dijkstra algorithm using the available network topology constructed from the information of adjacent routers informed by the CC Responses. r_n is the ratio of Interests generated from router n of $\boldsymbol{R}_a$, and r_n is derived by $r_n = Y_n / \sum_{j \in \boldsymbol{R}_a} Y_j$ using Y_j informed by the CC Reponses. When multiple routers are candidates of x_m, one of them is randomly selected. Although the IR needs to select x_m for all the content of $\boldsymbol{M}_f$, x_m is independent of those of other content items of $\boldsymbol{M}_f$. Therefore, the IR can obtain x_m with the calculation time of $O(R_a C_m)$ even if the IR checks all the candidates of $\boldsymbol{C}_m$, where $R_a \equiv |\boldsymbol{R}_a|$ and $C_m \equiv |\boldsymbol{C}_m|$.

C. Promotion Process for Original

Using the PLO (Promotion List for Original) Interest, the IR notifies all the routers of $\boldsymbol{R}_a$ of x_m selected for each content of $\boldsymbol{M}_f$. Like the CC Interest, the PLO Interest is transferred by exploration. Router n receiving the PLO Interest checks the PLO and promotes copies cached in its CS to originals for all content m with $x_m = n$. In other words, router n moves these copies from CS to the memory for originals if it is implemented, or router n sets the perpetual flag $f_m = 1$ for these copies. Next, router n advertises the names of content with $x_m = n$ promoted to originals to adjacent routers by the Prefix LSA. As a result, the entries of these content items are created at FIBs of routers $\boldsymbol{R}_a$, and the availability of these content items is recovered, i.e., Interests can be forwarded from routers $\boldsymbol{R}_a$ to the promoted originals.

Routers which completes the promotion process send the PLO Response to the IR in the same way as the CC Response, and the PLO Response includes the list of content names whose availability are successfully recovered. The IR checks the PLO Response returned from each router. For content whose availability is fail to be recovered for any reason, the IR reselects the copy promoted to original and sends the PLO Interest if other routers cache the content.

D. Avoiding Duplicated Selection of Promoted Copies

If there are multiple operating routers adjacent to failed routers, multiple routers might start the process recovering the content availability as the IRs. To avoid this, we assume that routers which receive the CC Interest sent from other routers do not become the IR nor send the CC Interest, even when detecting the loss of connectivity with adjacent routers. However, if routers detect the network failure before the CC Interest sent by other routers arrive at them, multiple routers will send the CC Interest as the IRs. Therefore, when an IR receives the CC Interest from other routers, the IR compares the timestamp of the CC Interest received with that of itself, and the IR selects and informs the copies promoted to originals only when the timestamp of itself is older than that of the received CC Interest. As a result, just a single router determines the location of copies promoted to originals for all the content of $\boldsymbol{M}_f$ as the IR.

V. Performance Evaluation

We show numerical results obtained by a computer simulation programed by ourselves using C language.

A. Evaluation Condition

The simulator consists of the initialization part and the request-generation part. In the initialization part, the request ratio of each content was configured, and the originals of content items were placed at routers (see Section V-A2). In the request-generation part, some routers and links were failed by network failure after 100,000 requests were sequentially generated (see Section V-A4). Moreover, 100,000 requests were also sequentially generated after content availability was recovered by the proposed CPO.

1) Network Topology: We used the backbone networks of four commercial ISPs in the USA, At Home Network, CAIS Internet, Allegiance Telecom, and Verio, whose PoP-level topologies are publicly available at the CAIDA website [5]. We assumed that one ICN-router was provided at each of the N PoPs. Let p_n denote the population ratio of node n, i.e., the population of node n divided by the total population of all the N nodes. Table I summarizes N, the node count, E, the link count, and H, the average hop distance between nodes weighted by their population ratios, i.e., $H = \sum_{i,j \in \boldsymbol{N},\, i \neq j} p_i p_j h_{i,j}$. We assumed that r_n, the ratio of requests generated from node n, agreed with p_n. We also assumed that the default path of Interests was the shortest-hop route from the node accommodating the requesting user to the node accommodating the original of the requested content. Therefore, H corresponds to the average hop length of delivery flows when content is delivered from the origin hosts without using caches.

We classified these networks into two types with different shapes. At Home Network and CAIS Internet were classified into a ladder type, in which no hub nodes existed, and packets needed to visit many intermediate nodes before arriving at destination nodes, so H was large. Allegiance Telecom and Verio were classified into a hub and spoke (H&S) type, in which several hub nodes connected with many other nodes existed. In H&S networks, packets can reach destination nodes with a small hop count by traversing through hub nodes, so H was small.

TABLE I
SUMMARY OF PROPERTIES OF FOUR NETWORKS EVALUATED

Network	N	E	H	Type
At Home Network	46	55	6.83	Ladder
CAIS Internet	37	44	5.49	Ladder
Allegiance Telecom	53	88	2.81	Hub & Spokes
Verio	35	72	2.23	Hub & Spokes

2) Content: We set M, the total content count, to 10,000. It has been reported that the request distribution of various types of digital content, e.g., websites and user-generated videos, obey the Zipf distribution [4][7]. For example, the request count of websites obeyed the Zipf distribution with a parameter θ between 0.64 and 0.83 [4] or between 0.74 and 0.84 [20]. The request count of YouTube videos obeyed the Zipf distribution with a parameter θ of about 0.8 [7]. Therefore, we assumed that $q(m)$, the request ratio of content m, obeyed the Zipf distribution with a parameter θ, and we assumed that parameter θ as well as the popularity rank of M content items were identical at all N routers. We set $\theta = 0.8$ without otherwise stated.

We assumed that the size of all M content items was identical, and B, the storage capacity of CS at each router, was also identical at all N routers. In a software-based ICN router, the maximum memory size of the content store was set to 256 Gbytes [24]. The average length of YouTube videos is about 4 minutes and 20 seconds [22], and the standard bitrate of YouTube videos using 2k quality is 10 Mbps. Therefore, the average size of YouTube videos is about 0.325 GBytes, so the content store of software-based ICN routers can store about 790 content items. Assuming that the content catalog of 10,000, the CS size was about 8%. Let b denote the normalized capacity of CS, i.e., $b = B/M$, and we set $b = 0.01$, i.e., $B = 100$, without otherwise stated. At the beginning of each simulation, we placed O_m, the original of content m, at a router randomly selected with the probability proportional to the population ratio p_n, and we did not change the location of O_m during the simulation. At the initial state, the CSes of all N routers were set to empty. We generated content requests sequentially at router n randomly selected with the probability of r_n for content m randomly selected with the probability of $q(m)$. We repeated ten trials with various O_m allocated by different random seeds, and we evaluated all the results by the average value over the ten trials.

3) Caching Strategies: For each request generated at router u for content m, the Interest was transferred to router o accommodating O_m on the default path, and content m was delivered from router s closest to router u among routers caching content m on the default path. If content m was not cached at all the routers on the default path, router o was the source router s. As the caching strategy at routers receiving content on the default path, we assumed the following five methods.

AllCache Content was simply cached at all routers on the default path from source router s to destination router u [8]. This method is also known as transparent en-route caching (TERC) [18] or universal caching [15].

EdgeCache Content was cached only at the last hop router on the default path, i.e., router u [29].

UniCache Content was cached at each router on the default path with the probability of $1/h_{s,u}$ [8], so content was cached at one router randomly selected on the default path between routers s and u on average.

ProbCache Content was cached at router c on the default path with the probability of $h_{s,c}/h_{s,u}$ [25]. In other words, content was cached at routers on the default path with the probability proportional to the distance from router s, so routers closer to router u were more likely to cache content.

LCD (leave copy down) Content was cached only at the next hop router from router s [19], and WAVE also took a similar approach with the unit of the chunk [8]. Copies of content tended to exist around router o, and they gradually spread over the network.

In all the five caching strategies, we used the LRU as the cache-replacement policy, and content m was never cached at router o accommodating O_m. To perpetually hold copies of content promoted to originals, we assumed that memories were provided at routers in addition to CS to keep copies promoted to originals, and the storage capacity of CS was unchanged. We did not bound the upper limit for the number of copies promoted to originals at each router.

4) Network Failure: We assumed that a large-scale network failure occurred just after content items were delivered for 100,000 requests. All routers within the area of circle with center of router n and with radius of D km were failed, and these routers were included in $\boldsymbol{R}_f$. When operating routers were divided into multiple areas disconnected, we evaluated only the area in which the number of operating routers was the largest, and $\boldsymbol{R}_a$ included only the operating routers in the selected area. Operating routers in the other disconnected areas were included in $\boldsymbol{R}_f$. When $D = 500$ km, for example, about 10% to 15% routers lost connectivity, and about 15% content items lost availability. In the following evaluation, we set $D = 500$ km without otherwise stated. In the computer simulation, we did not explicitly consider the location of the IR and executed only the selection process of copies promoted to originals described in Section IV-B among the processes of CPO described in Section IV. For the given radius of network failure D, we repeated N failure scenarios in which each of

N routers was the center of network failure, and we evaluated all the metrics by the average over N trials.

B. Effect Recovering Content Availability

In all the evaluations shown in this section, the results obtained in At Home Network and Verio similar with those obtained in CAIS Internet, so we show only the results obtained in CAIS Internet and Allegiance Telecom. Figure 2 shows Φ_c, the recover ratio of content availability, against b, the normalized capacity of CS, θ, the Zipf parameter of content-popularity distribution, and D, the failure radius, in each caching strategy. We define Φ_c as the ratio of content items whose copies existed at one or more operating routers $\boldsymbol{R}_a$ and whose availability can be recovered by the CPO among all the unavailable content $\boldsymbol{M}_f$.

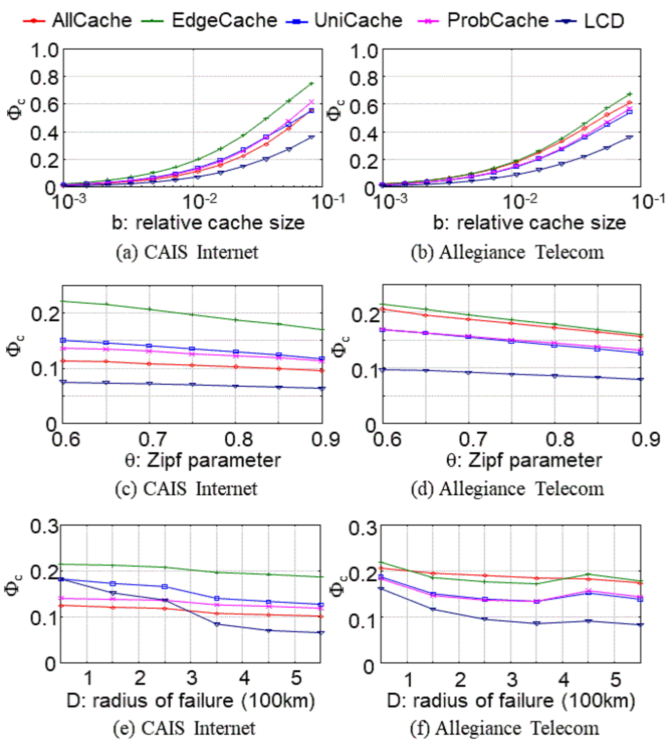

Fig. 2. Recover ratio of content availability by CPO

As b increased, the number of cached copies of each content increased, and Φ_c was improved. As θ increased, more content requests concentrated on a smaller number of most popular content items, so the number of cached copies of popular content increased, whereas that of unpopular content decreased. As a result, the number of content items whose copies cached at one or more operating routers decreased, and Φ_c decreased as θ increased. In LCD, content items were cached nearby their originals, so copies of unavailable content were likely to be lost as well, and Φ_c was small. In EdgeCache, content items were cached at routers located far from their originals, so Φ_c was the largest among the five caching strategies.

Although Φ_c of AllCache was the second largest in Allegiance Telecom, it was the second smallest in the other three networks. Only in Allegiance Telecom, the ratio of nodes with degree of unity, i.e., connecting with just one node, was large; it was about 0.17 in Allegiance Telecom, whereas it was about 0.05 to 0.08 in the other three networks. Nodes with degree of unity were not used for transferring content to users accommodated at other routers, so the frequency of cache replacement was low at these nodes, and Φ_c of AllCache was large in Allegiance Telecom. As D increased, the number of operating routers $\boldsymbol{R}_a$ decreased, so Φ_c decreased because the probability that one or more copies existed at $\boldsymbol{R}_a$ decreased. In LCD, Φ_c rapidly decreased with increase of D because copies tended to be cached close to originals.

C. Comparing Methods to Select Copies Promoted to Originals

To confirm the effectiveness of the CPO in selecting the location of copies promoted to originals, we evaluate the average hop length of delivery flows after recovering the content availability. We compare the results of the CPO with the case named *RND*. For each unavailable content m, the RND randomly selected one router among $\boldsymbol{C}_m$, i.e., operating routers storing copies of content m, as the copy promoted to the original of m. Figure 3 plots the average flow hop length of all the requests for content items whose availability was recovered by the CPO or RND. The average flow hop length of CPO was reduced by about 3% to 6% in CAIS Internet and by about 6% to 8% in Allegiance Telecom, compared with the RND.

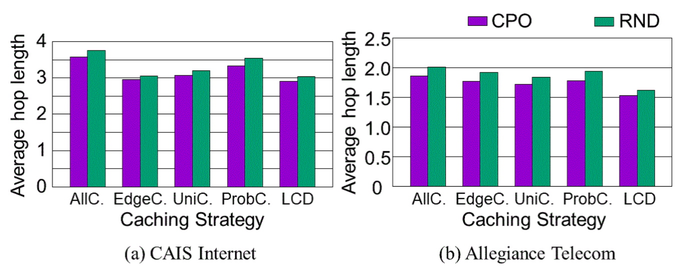

Fig. 3. Average hop length from source routers to users of content whose availability was recovered by CPO or RND

VI. Conclusion

In this paper, we proposed the CPO which recovers the availability of content by promoting one copy cached at an operating router to the original. We proposed the detail of the process in which one operating router centrally selected one copy promoted to original for all the unavailable content items. We also proposed the selection method of copies promoted to originals which minimized the average hop length of delivery flows. Through the computer simulation using the network topologies of backbone ISPs, we clarified that the availability of about 5% to 20% unavailable content items were recovered, when cache memory with the capacity of about 1% of total content was provided at each router. We also confirmed that the proposed CPO reduced the average hop length of delivery flows after recovering the content availability by several percent compared with the case randomly selecting the copies promoted to originals. If copies promoted to originals concentrate at specific routers, congestion will occur at these routers and the network links around them. Therefore, we will investigate the selection method of copies promoted to originals with considering the load balancing as well in future. Moreover, we will also investigate a decentralized approach, i.e., multiple routers autonomously promoting their cached copies to originals.

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