# Analysis of Content Availability at Network Failure in Information-Centric Networking

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***Abstract*—In recent years, ICN (Information-Centric Networking) has been under the spotlight as a network that mainly focuses on transmitted and received data rather than on the hosts that transmit and receive data. Generally, the communication networks such as ICNs are required to be robust against network failures caused by attacks and disasters. One of the metrics for the robustness of conventional host-centric networks, e.g., TCP/IP network, is *reachability* between nodes in the network after network failures, whereas the key metric for the robustness of ICNs is *content availability*. In this paper, we focus on an arbitrary ICN network and derive the content availability for a given probability of node removal. Especially, we analytically obtain the average content availability over an entire network in the case where just a single path from a node to a repository, i.e., contents server, storing contents is available and where multiple paths to the repository are available, respectively. Furthermore, through several numerical evaluations, we investigate the effect of the structure of network topology as well as the pattern and scale of the network failures on the content availability in ICN. Our findings include that, regardless of patterns of network failures, the content availability is significantly improved by caching contents at routers and using multiple paths, and that the content availability is more degraded at cluster-based node removal compared with random node removal.**

***Index Terms*—Content availability, information-centric networking (ICN), network failure, network robustness, node removal.**

## I. Introduction

In recent years, ICN (Information-Centric Networking) has gathered wide attention as a network that mainly focuses on transmitted and received data rather than on the hosts that transmit and receive data [1]. Two of promising network architectures for realizing ICN are CCN (Content-Centric Networking) [2] and NDN (Named Data Networking) [3]. In ICNs such as CCN and NDN, routers in a network can cache forwarded data to their own buffer memory. Thus, users can acquire data not only from a repository, i.e., content server, but also from routers. As a result, in ICNs, we can expect to reduce the content delivery delay and improve the content availability at failures of networks or hosts.

Generally, the communication networks such as ICNs are required to be robust against the network failures caused by attacks and disasters. For this reason, it is necessary to improve the robustness of the network so that the function of the network is not easily lost even if a network failure occurs. In other words, the networks need to maintain their network functions as much as possible even if a part of routers/links are broken due to a network failure. One of the most used metrics for the robustness of conventional host-centric networks, e.g., TCP/IP network, is *reachability* between nodes in the networks after the network failures, whereas the key metric of the robustness of ICNs is *content availability*. Because ICN is a cache network, users can still obtain contents from normally-operating routers even if the network is fragmented into multiple parts due to network failures. Therefore, in ICNs, the important metric of robustness is not how much the network is connected but how much contents can be obtained.

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However, because ICN is a more complicated network architecture compared to conventional host-centric networks, it is not easy to analyze the content availability at network failures in ICN. For instance, in simulation-based approaches, it is required to simulate the behavior of contents delivery in ICN as well as the behavior of the network failures. Thus, analyzing the content availability at network failures requires high computational complexity because simulation experiments have to be performed while changing combinations of several factors, e.g., the network topology as well as the pattern and scale of network failures.

The content availability at network failures in ICN has been analyzed mathematically [4, 5]. However, the network topologies and the patterns of network failures focused in these studies were limited, so the content availability at network failures in ICN has not been fully understood. Moreover, in the past studies on the robustness of networks, it is widely known that factors such as the network topology and the network failure pattern, e.g., random node removal and adversary attack to nodes, highly affect the robustness of networks (see, for instance, [6]). For this reason, the content availability at network failure should be analyzed considering both these factors and ICN-specific factors, e.g., content request distribution.

In this paper, we focus on an arbitrary ICN network and derive the content availability for a given probability of node removal. Especially, by extending the performance analysis of ICN [4], we analytically obtain the average content availability over the entire network in the case where just a single path from a node to the repository storing contents is available as well as the case where multiple paths to the repository are available, respectively. Furthermore, through several numerical evaluations, we investigate the effect of the structure of network topology as well as the pattern and scale of network failure on the content availability in ICN.

This paper is organized as follows. First, Section II introduces previous works investigating the robustness of networks including ICNs. Section III presents our analytical model and derives the content availability at network failures in ICN. Section IV analyzes the content availability in ICN while changing the structure of network topology as well as the pattern and scale of network failures. Finally, Section V provides the summary of this paper and discusses future works.

## II. Related Work

Network robustness is one of the major research topics in the field of graph theory and network science. Past studies have investigated how the network connectivity is lost due to the removal of nodes and links in a network through the mathematical and experimental approaches. In the network science, it has been discussed how the scale-free property of network topology affect the robustness of networks [6, 7]. The authors of [6] obtained the diameter of a network and the size of the largest connected-component when nodes in the network are removed based on a given pattern of node removal. Consequently, they revealed that, compared to random networks, the scale-free network is highly-tolerant against the random node removal, whereas the scale-free network is vulnerable against the adversary attack. These are one of the major findings in the field of network science.

In recent years, a few studies have analyzed the content availability at network failures in ICN to clarify the robustness of ICNs [4, 5]. The authors of [4] focused on an arbitrary network topology of ICN and derived the content availability when the link failure rate was given. Through numerical evaluations, it was shown that the availability of frequently-requested contents can be improved by content caching in ICN. The authors of [5] derived the content availability in the hierarchical network topology. By obtaining the content availability while changing the link failure rate in the middle-scale hierarchical network topology called as IPTV-like network topology in [5], they showed that the content availability can be improved by about 10% when the link failure rate was large. However, these studies focused on the content availability *just after* a network failure. Even though path(s) in a network are broken due to a network failure, the reachability of a path to the repository might be recovered by utilizing an alternative path discovered with a routing protocol, e.g., NLSR (Named-data Link State Routing Protocol) [8]. Therefore, in this paper, by deriving the content availability with the case of multiple paths as well as a single path, we analyze the content availability considering the behavior of the routing protocol after a network failure.

In addition to the analyses of the content availability at network failures in ICN, several methods for recovering the availability of contents whose availability was lost due to network failures have been proposed [9, 10]. The author of [10] considered a situation where the availability of contents stored in the repository was lost because of network failures. Also, the author proposed a method to promote a content replica cached at operating routers to the original and update forwarding tables at routers so that request packets were appropriately forwarded to the router newly promoted to the original. Through simulations, it was shown that the availability of about 5%–20% of contents whose availability was lost can be recovered with the proposed method.

## III. Analysis

In this section, by extending our performance analysis of ICN on an arbitrary network topology [4], we derive the content availability at network failure in ICN. Please refer to [4] for the details.

### A. Network Model

An ICN network consists of multiple routers and multiple repositories, and it is represented by an undirected graph $G = (V, E)$ as shown in Fig. 1. Hereafter, we simply call router and repository as *node*. We define $\mathcal{C}$ as a set of contents in a network, and we assume that the cache size of all routers is $B$. It is supposed that each entity, i.e., content requester, is connected to a node, and an entity connected to node $v$ repeatedly requests content $c$ of $\mathcal{C}$ with the request rate of $\lambda_{c,v}$.

We consider $K$ path candidates from node $v$ to repository $s_c$ storing content $c$, and we define $\mathcal{P}_v^c$ as the set of these $K$ paths. Here, $\mathcal{P}_v^c[k]$ indicates $k$-th path in $\mathcal{P}_v^c$. Unless explicitly stated, we assume that forwarding tables at nodes, i.e., FIB (Forwarding Information Base) in CCN [2] and NDN [3], are configured so that a path is preferentially selected according to the order of element numbers, so the first path of $\mathcal{P}_v^c[1]$ in the path candidates is the default path. We note that in any path candidates, $P[1]$ and $P[|P|]$ are node $v$ and repository $s_c$, respectively, where $|P|$ indicates the size of path $P$, i.e., the number of nodes comprising path $P$.

In this paper, we focus on the node removal as network failure, and we define $r_v$ as the probability that node $v$ is removed from the network due to network failures. We note that the repositories are never removed due to network failures, so $r_{s_c} = 0$ for $c \in \mathcal{C}$. We also assume that the bandwidth of all links are sufficiently large, and any losses of request/response packets does not occur due to a buffer overflow at nodes.

### B. Content Availability

First, we formulate the content availability at a network failure in ICN. In this paper, we define the content availability as the probability that requesters can obtain the target contents when requesting them. The average content availability over the entire network is denoted as $A$. Also, the availability of content $c$ at node $v$ is denoted as $A_v^c$. In Sections III-C and III-D, we derive the content availability when just a single path exists, and when multiple paths exist, respectively.

The average content availability at node $v$, $A_v$, is given by the weighted average of request rate $\lambda_{c,v}$ for content $c$ at node $v$ and the availability $A_v^c$ of content $c$ at node $v$ [4], so we have

$$A_v = \sum_{c \in \mathcal{C}} \frac{\lambda_{c,v} \, A_v^c}{\sum_{c' \in \mathcal{C}} \lambda_{c',v}}. \tag{1}$$

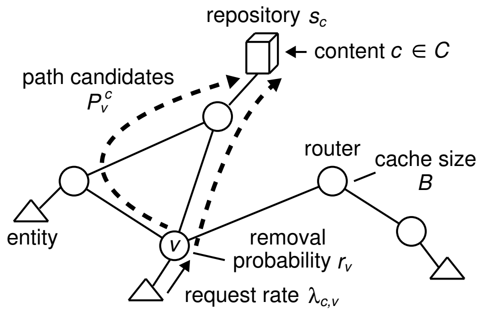



Fig. 1. Analytical model

Using the number of nodes $N(=|V|)$, the average content availability over the entire network $A$ is given by

$$A = \frac{\sum_{v \in V} A_v}{N}. \quad (2)$$

### C. Content Availability When Just Single Path Exists

Next, we derive the content availability at a network failure when just a single path exists from each entity to each repository, i.e., $K = 1$. The content availability in this case agrees with that without changing path from the default path at the network failure. We consider the availability of content $c$ at node $v$, $A_v^c(P)$, when path $P$ from node $v$ to repository $s_c$ storing content $c$ is given.

Let $\eta_v^c(P, n)$ denotes the probability that a response packet for request of content $c$ from node $v$ is returned from $n$-th node on path $P$. When there is a cache hit on $n$-th node without any cache hits at any routers on path $P$ between the first and $n-1$-th nodes from node $v$, the content is returned from $n$-th node, i.e., router or repository. Therefore, using the cache hit probability $q_{c,v}$ for content $c$ at node $v$, we have the following equation [4],

$$\eta_v^c(P, n) = q_{c,P[n]} \prod_{i=1}^{n-1} (1 - q_{c,P[i]}). \quad (3)$$

When a cache replacement algorithm is either LRU (Least-Recently Used) or FIFO (First-In First-Out), the cache hit probability of each router in the network can be approximately calculated using the MCA (Multi-Cache Approximation) algorithm [11].

Let $\rho(P, n)$ denotes the probability that a part of path $P$ from the first node to the $n$-th node is available after a part of nodes are removed due to a network failure, and $\rho(P, n)$ is given by

$$\rho(P, n) = \prod_{i=1}^{n} (1 - r_{P[i]}). \quad (4)$$

Node $v$ can successfully obtain the content after nodes are removed from the network only when all nodes from node $v$ to the node returning content $c$ are available on path $P$. For this reason, by using $\eta_v^c(P, n)$, the probability that the $n$-th node returns content $c$, and $\rho(P, n)$, the probability that a path to the $n$-th node is available, we have $A_v^c(P)$ as

$$A_v^c(P) = \sum_{n=1}^{|P|} \eta_v^c(P, n)\, \rho(P, n). \quad (5)$$

Therefore, when a single path, i.e., the default path, $\mathcal{P}_v^c[1]$ is given, the availability $A_v^c$ for content $c$ at node $v$ is given by $A_v^c(\mathcal{P}_v^c[1])$.

### D. Content Availability When Multiple Paths Exist

Finally, we derive the content availability when multiple paths from a node to a repository storing contents exist, i.e., $K \geq 2$. Let $R_{c,v}$ denotes the probability that a request packet for content $c$ sent from node $v$ can arrive at the repository through any paths included in $\mathcal{P}_v^c$ after a network failure. In this paper, only when one or more paths of $\mathcal{P}_v^c$ are reachable to the repository, we regard that the reachability to content $c$ from node $v$ is satisfied. When the reachability to the repository on all the path candidates in $\mathcal{P}_v^c$ is lost, the content is available only when content $c$ is cached at any nodes to which the reachability from node $v$ is maintained. For simplicity, we assume that the default path, $\mathcal{P}_v^c[1]$, is used in this case.

After a network failure occurs, when any intermediate nodes except for the first and the $|P|-1$-st nodes, i.e., node connected to the repository, are removed on the $k$-th path $P$, i.e., $\mathcal{P}_v^c[k]$, the $k+1$-st path becomes a candidate of the alternative path. $\psi(P)$, the probability that path $P \in \mathcal{P}_v^c$ is fragmented by removing any intermediate nodes, i.e., the second to the $|P|-2$-nd nodes on path $P$, is given by

$$\psi(P) = 1 - \prod_{i=2}^{|P|-2} (1 - r_{P[i]}), \quad (6)$$

where $r_{P[i]}$ is the removal probability of the $i$-th node on path $P$.

We define $R_{c,v}^k$ as the probability that all the first to the $k-1$-st paths in $\mathcal{P}_c^v$ are broken, and the $k$-th path is available, and it is given by

$$R_{c,v}^k = \phi(\mathcal{P}_v^c[k]) \prod_{i=1}^{k-1} \psi(\mathcal{P}_v^c[i]). \quad (7)$$

In the above equation, $\phi(P)$ is the probability that path $P$ is established, i.e., all nodes on path $P$ are not removed, so $\phi(P) = \prod_{i=1}^{|P|} (1 - r_{P[i]})$.

Because the reachability $R_v^c$ for content $c$ at node $v$ is the probability that any path of path candidates $\mathcal{P}_v^c$ is available, we have

$$R_{c,v} = \sum_{k=1}^{K} R_{c,v}^k. \quad (8)$$

When multiple paths can be used, contents are available in one of the two cases: (i) returning contents from the repository, and (ii) returning contents from caches at nodes. If the reachability to the repository is maintained, the probability that the content is available is unity. On the other hand, if the reachability to the repository is lost, the content is available only when path excluding the repository on the default path is available. Therefore, the content availability with multiple paths $A_v^c$ is given by

$$A_v^c = 1 \times R_{c,v} + A_v^c(P^*) \times (1 - R_{c,v}), \quad (9)$$

where $P^*$ is a path excluding the repository from default path $\mathcal{P}_v^c[1]$.

## IV. Numerical Evaluation

In this section, we numerically investigate the influence of the pattern and the scale of network failures as well as the structure of network topology on the content availability at network failure in ICN.

### A. Parameter Settings

In the numerical evaluation, we used three types of synthetic network topologies, i.e., random network, tree-like topology, and grid topology. Table I summarizes the properties of network topologies used in the numerical evaluation. To investigate the influence of the pattern of network failures with considering the distance between nodes, nodes were distributed in a $1 \times 1$ square field in the three types of synthetic network topologies.

The details of network topologies used in the numerical evaluation are as follows.

- Random network
  By using a network generation model which is an extension of the ER (Erdõs-Rényi) model [12], we generated a random network based on distance between nodes. Given the number of nodes $N$ and the average degree $\overline{k}$, a random network was generated as follows; (1) $N$ nodes were randomly distributed in the plane square field with a uniform distribution, (2) distance $d(u, v)$ for all node pairs were calculated, (3) a node pair $(u, v)$ was randomly selected according to the probability proportional to $1/d(u, v)^\theta$, and a link was added between the randomly-selected node pair $(u, v)$, and (4) until the number of links was $|E| (= N\,\overline{k}/2)$, step (3) was repeated. Here, $\theta\,(0 \leq \theta \leq 1)$ in step (3) is a parameter that adjusts the effect of distance between nodes. In the case of $\theta = 0$, node pairs were selected with the identical probability, so this network-generation model is equivalent to the ER model. In the numerical evaluation, multiple network instances with $N = 100$ and $\overline{k} = 4$ were generated, and only a *connected* network instance was used among generated network instances.
- Tree-like topology
  A network based on the tree topology was generated as follows; (1) for a given $m$ and tree height $h_{max}$, a perfect $m$-ary tree was generated, (2) a root node of the tree was placed at the center of the field, and leaf nodes located at $h$-th level were uniformly placed along a circumference with radius $(h-1)/h_{max}$, (3) until the number of nodes was $N$, it was repeated that leaf nodes located at $h_{max}$-th level were randomly removed, and (4) based on the link addition probability $p$, links between closest nodes located at $h$-th level were randomly added. Tree-like topology with $p = 0$ is perfect $m$-ary tree, which is generally used in the field of performance evaluation of ICN [13]. However, in the numerical evaluation, we considered the content availability with multiple paths from a node to a repository, so we used the tree-like topology with $p = 0.5$.
- Grid topology
  We used a uniform grid topology with $10 \times 10$. In the grid topology, all nodes were uniformly distributed in the field.

For a given network topology, just a single repository was attached to the node whose degree was the highest, and 1,000 contents were stored in the repository. Hence, in the tree-like topologies, the repository was attached to the root node of the tree. Each entity repeatedly requested contents stored in the repository. The request-generation rate $\lambda_{c,v}$ for content $c$ from entities at node $v$, was given by the Zipf distribution with the exponent parameter of 0.8 which was used in [5, 10] for instance.

The cache-replacement algorithm at nodes was LRU, and the cache size of nodes $B$ was varied from 0 to 100 contents. For a given condition of the network topology and the cache size, we obtained the cache hit probability $q_{c,v}$ for content $c$ at node $v$ using the MCA algorithm [11]. The path candidates $\mathcal{P}_v^c$ from node $v$ to the repository storing content $c$ was given by $K$ paths with the shortest path length among all paths from node $v$ to the repository. We note that the path was selected based on the identifier of nodes if multiple paths with the same path length existed.

We considered two types of network-failure patterns, *random node removal* and *cluster-based node removal*, and we set the removal probability $r_v$ of node $v$ according to the pattern of network failures.

- Random node removal
  This corresponded to the random-failure scenario of routers, that is, removing randomly-chosen nodes in the network. The removal probability $r_v$ of node $v$ was identically set to $r$.
- Cluster-based node removal
  This corresponded to the destruction of routers and links due to a disaster, that is, removing all nodes within a circle with radius $D$ from a center of a network failure. For failure radius $D$, removal probability $r_v$ of node $v$ in a given network topology was calculated as follows. First, we denoted $V_u^D$ as a set of nodes within a circle with radius $D$ from node $u$ which is a center of a network failure. A binary function $\delta_u^D(v)$, which implied whether node $v$ was included in a set of nodes $V_u^D$, can be represented as

$$\delta_u^D(v) = \begin{cases} 1 & \text{if } v \in V_u^D \\ 0 & \text{otherwise} \end{cases}. \quad (10)$$

TABLE I
PROPERTIES OF NETWORK TOPOLOGIES USED IN NUMERICAL EVALUATION

| | random network | | | tree-like topology ($p = 0.5$) | | grid topology |
|---|---|---|---|---|---|---|
| | $\theta = 0$ | $\theta = 0.5$ | $\theta = 1$ | $m = 2$ | $m = 3$ | |
| number of nodes | 100 | 100 | 100 | 100 | 100 | 100 |
| number of links | 200 | 200 | 200 | 144 | 143 | 180 |
| average degree | 4.00 | 4.00 | 4.00 | 2.88 | 2.86 | 3.60 |
| standard deviation in degree | 2.06 | 1.76 | 2.00 | 1.21 | 1.31 | 0.57 |
| average path length | 2.75 | 2.39 | 2.57 | 3.36 | 2.47 | 5.82 |
| clustering coefficient | 0.04 | 0.03 | 0.05 | 0.23 | 0.38 | 0.00 |

Then, the node-removal probability $r_v$ was set to the average of presence or absence of the node removal while changing node $u$, i.e., the center of network failure, to all nodes using the binary function $\delta_u^D(v)$;

$$r_v = \frac{\sum_{u \in V} \delta_u^D(v)}{N}. \tag{11}$$

### B. Evaluation Results

*1) Content Availability at Random Node Removal:* First, Fig. 2 shows the average content availability over the entire network when changing the node removal probability in random network with $\theta = 0$. Figures 2(a) and 2(b) show the content availability with a single path and that with multiple paths, respectively. To explicitly show how much the content availability was improved by utilizing multiple paths, the improvement ratio of the content availability, i.e., the content availability with multiple paths divided by the content availability with a single path, is shown in Fig. 2(c). In these figures, results for various cache sizes $B$ of routers are plotted.

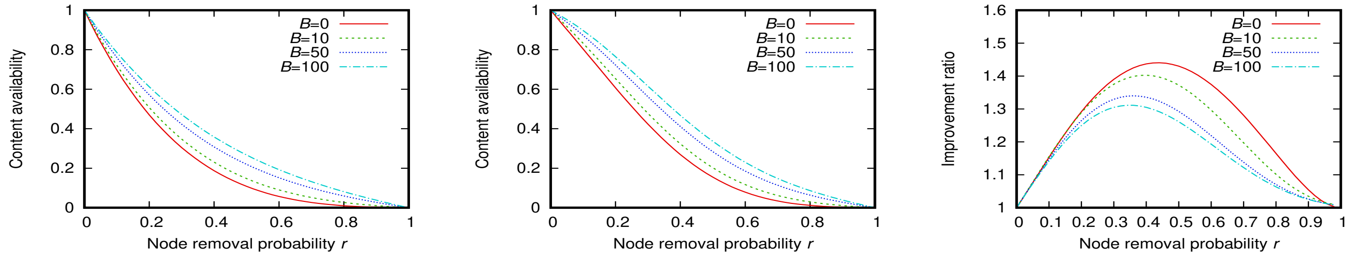
From Figs. 2(a) and 2(b), we confirm that the average content availability over the entire network rapidly decreased with the increase of the node removal probability. Also, we found that the content availability was significantly improved compared with the network availability, i.e., the content availability at $B = 0$, when the cache size was large, e.g., $B = 50$ and $B = 100$. In contrast, when the cache size was small, e.g., $B = 10$, the content availability was not highly improved. Moreover, Fig. 2(c) clearly illustrates that the content availability can be improved by utilizing multiple paths regardless of the cache size of nodes. This was because that the content availability was recovered by using alternative paths that can reach the repository from nodes even if default paths are fragmented by node removal. Because of content caching in ICNs, frequently-requested popular contents were returned from nodes with high probability. However, infrequently-requested unpopular contents were returned from the repository storing the corresponding content in many cases. For this reason, by recovering the reachability to the repository using the alternative paths, the average content availability can be improved. We should note that using the alternative path instead of a given default path might lead to increase the number of hops required to acquire contents.

*2) Content Availability at Cluster-Based Node Removal:* Figure 3 shows the content availability over the entire network when changing the radius of network failure in random network with $\theta = 0$. Similar to the case of random node removal (Fig. 2), Figs. 3(a) and 3(b) show the content availability with a single path and that with multiple paths, respectively. Also, the improvement ratio in the content availability with multiple paths is shown in Fig. 3(c).

From Figs. 3(a) and 3(b), the content availability over the entire network was rapidly degraded as the radius of network failure increased. By comparing the content availability with the cluster-based node removal and that with the random node removal, we found that the content availability at the cluster-based node removal was much smaller than that at the random node removal. This implies that the content availability over the entire network was more likely to be lost when many nodes located closely were removed at the same time. Hence, similar to the case of random node removal, the content availability at the cluster-based node removal can be also improved by using both the content caching and multiple paths.

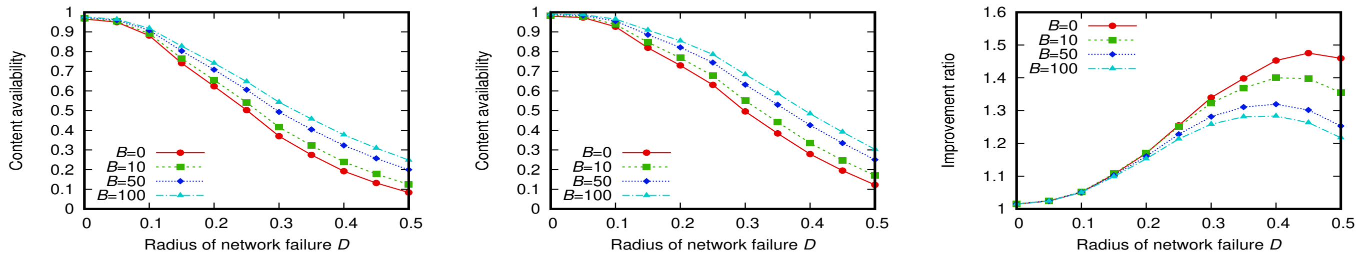
*3) Effect of Network Topology on Content Availability:* Finally, we discuss the effect of the structure of network topology on the content availability at network failure. Figures 4 and 5 show the content availability over the entire network at the random node removal and the cluster-based node removal, respectively. In these figures, we show results of various network topologies where *random*, *tree*, and *grid* indicate the results in random network, tree-like topologies, and grid topology, respectively. We note that we obtained almost the same results with different values of $\theta$ in random networks, so we plot only the results with $\theta = 0$ in random network.

In the random node removal, the content availability in the tree-like topology with $m = 2$ and the grid topology was much smaller than those in the tree-like topology with $m = 3$ and the random network. Because the average path lengths of tree-like topology with $m = 2$ and the grid topology were longer than those of the other network topologies, default paths were more likely to be fragmented. So, the content availability with a single path in the tree-like topology with $m = 2$ and the grid topology were small. However, in the tree-like topology with $m = 2$ and the grid topology, the content availability were significantly improved when the node removal probability was low, and the failure radius was small because of the existence of multiple and reachable alternative paths.



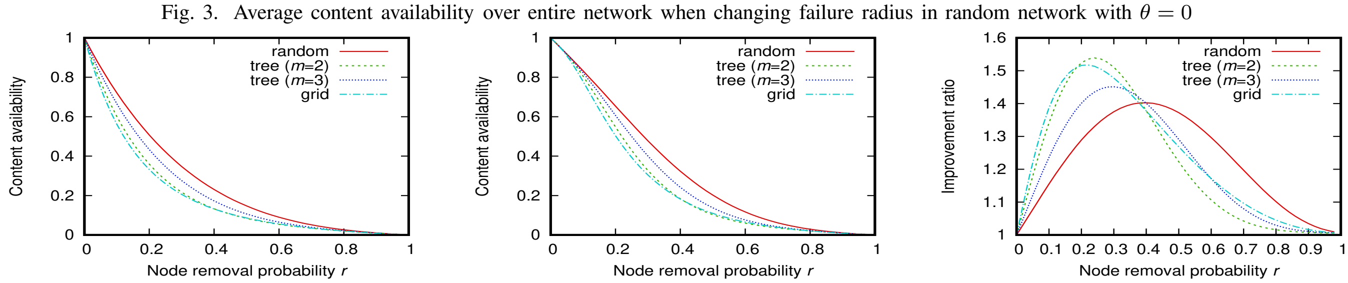

(a) content availability with single path (b) content availability with multiple paths (c) improvement ratio

Fig. 2. Average content availability over entire network when changing node removal probability in random network with $\theta = 0$



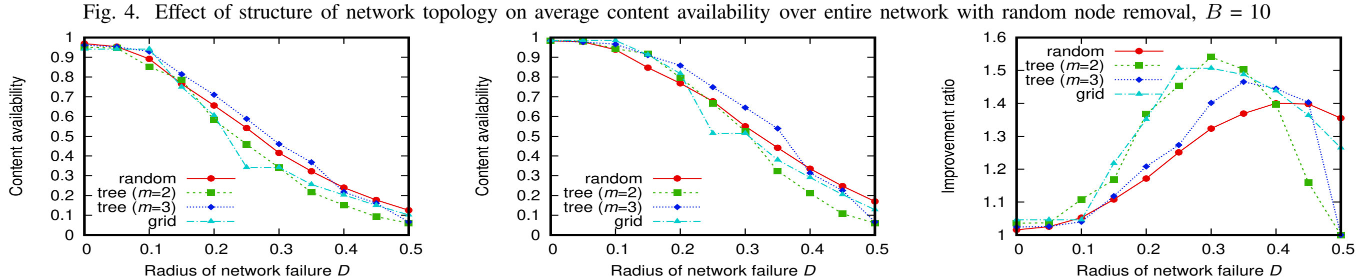

(a) content availability with single path (b) content availability with multiple paths (c) improvement ratio

Fig. 3. Average content availability over entire network when changing failure radius in random network with $\theta = 0$




(a) content availability with a single path (b) content availability with multiple paths (c) improvement ratio

Fig. 4. Effect of structure of network topology on average content availability over entire network with random node removal, $B = 10$




(a) content availability with single path (b) content availability with multiple paths (c) improvement ratio

Fig. 5. Effect of structure of network topology on average content availability over entire network with cluster-based node removal, $B = 10$

## V. Conclusion

In this paper, by extending the performance analysis of ICN [4], we derived the content availability at a network failure in ICN. For an arbitrary ICN network topology, we derived the content availability over the entire network when just a single path from a node to the repository was available and when multiple paths from a node to the repository were available. Moreover, through numerical evaluations, we investigated the influence of the structure of network topology as well as the pattern and scale of network failure on the content availability in ICN. We showed that regardless of patterns of network failures, the content availability can be significantly improved using the content caching and multiple paths, and that the content availability at the cluster-based node removal was lower than that at the random node removal.

As future works, we are planning to approximately analyze the content availability in large-scale ICN networks and design the caching and routing methods based on the analysis.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