Efficient User-Assisted Content Distribution over Information-Centric Network

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Abstract. To solve the fundamental limitations of current Internet in supporting today's content-oriented services, information-centric networking (ICN) concept has been proposed. ICN has attractive features (e.g., name-based routing, in-network caching and multicast) supporting efficient content-oriented services. However, the attractive features may not be fully utilized by all existing contents due to the resources limitation, which means additional technique may be required for improving content-oriented services. In this paper, as one possible way for this, we examine P2P technique exploiting user resources in ICN. We first examine how P2P looks like in ICN. Then, we introduce the contribution-aware ICN and corresponding incentive mechanism to utilize the user resources efficiently. We also show how the contribution-aware ICN can be implemented over the existing ICN architectures. Through simulations, we evaluate an effect of user participation on the content distribution performance in ICN. We also verify the feasibility of the contribution-aware ICN in terms of resources utilization efficiency.

Keywords: Information-centric networking, user-assisted content distribution, P2P, incentive mechanism.

1 Introduction

Current Internet (supporting communications between any pair of machines identified with an IP address) has fundamental limitations in supporting today's content-oriented services (caring about the content itself rather than the IP address of content source). To fundamentally address the mismatch between the current Internet and the today's content-oriented services, ICN [2]-[8] has been proposed as one architecture for future Internet. As a revolutionary approach, ICN replaces addressed machines with named contents in the network level and includes some add-on functions of the current Internet (e.g., multicast and caching) as native in-network functions. For example, in ICN, a user just needs to specify a content name that it wants to download. Then, ICN satisfies the user request with data from any source storing a copy of the content, enabling efficient caching as part of the network service.

Even though ICN supporting attractive features is well suited for efficient content-oriented services, all existing contents may not be able to fully utilize the

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attractive features of ICN. For example, the in-network caching may be only useful for some popular contents due to the limited size of cache. Then, we may need additional approach for improving the content-oriented services in case of contents that cannot fully utilize the attractive features of ICN. As one possible way for this, in this paper, we focus on P2P technique exploiting user resources (i.e., user-assisted content distribution) with proper incentive mechanism. In particular, we argue that 1) P2P technique exploiting user resources will be still useful for content distribution in ICN as the case of current Internet and 2) existing ICN architecture needs to be extended to utilize the user resources efficiently.

To this end, we introduce the contribution-aware ICN (where the contribution-related information is added to both users and contents) to utilize the user resources efficiently in ICN. A contribution of each user in terms of content distribution is managed by the contribution-aware ICN. In addition, the content is published with a required contribution level that needs to be satisfied by a user who wants to download the content. Therefore, a request of user with enough contribution is only handled so as to encourage the users to contribute their resources. Through simulations, we first show that the user participation has significant impact on the content distribution in ICN, especially when the content cannot fully benefit from the features of ICN (i.e., the in-network caching in our simulation). We also show that the contribution-aware ICN can utilize the user resources efficiently and improve the content distribution performance by using the explicit contribution-related information of users and contents.

This paper is organized as follows. In Section 2, we introduce main features of ICN and discuss its implications on challenging issues of current P2P content distribution. From this, we identify one important research issue in ICN: how to utilize the user resources efficiently. Then, we introduce the contribution-aware ICN in Section 3. We also discuss how the contribution-aware ICN can be implemented over existing ICN architectures. We discuss the incentive mechanism that can be used in the contribution-aware ICN in Section 4. After evaluating the feasibility of the contribution-aware ICN in Section 5, we conclude this paper in Section 6.

2 Contribution-Aware ICN

In this Section, we introduce the contribution-aware ICN architecture to incentivize the user-assisted content distribution in ICN. The user resources will be still useful in ICN, because all existing contents may not be able to fully utilize the attractive features of ICN. For example, the in-network caching is strictly on an opportunistic basis. A cached content can be deleted at any time based on replacement policy such as Least Recently Used (LRU), since the cache size is limited. Due to this reason, only some popular contents can be cached. The native multicast support may be only meaningful for real-time streaming where users are watching same part of content at the same time. Then, the contents that cannot leverage the attractive features of ICN will be provided through a client-server model that is not so efficient in distributing contents unless additional resources (e.g., dedicated servers of CDN and user resources of P2P in the

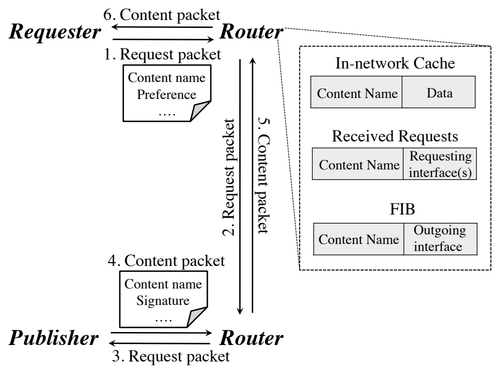


Fig. 1. Conceptual illustration of ICN

current Internet) are utilized. Therefore, we posit that the user resources can be utilized for improving the content distribution in ICN as P2P utilizes the user resources in the current Internet.

2.1 P2P Content Distribution in ICN

Before discussing the contribution-aware ICN trying to utilize the user resources in detail, we first identify one challenging research issue when the P2P technique exploiting the user resources is applied into ICN.

Features of ICN

Even though each existing ICN proposal has different details, there are common features characterizing ICN as follows (Fig. 1)[1]:

- Content has an *unique identifier* decoupled from its location. When a user wants to download a content, the user just needs to issue a content request including the content name instead of its location (e.g., URL of the current Internet). The location-independent content identifier enables efficient caching as the in-network service.
- *Name-based (anycast) routing* forwards the user request specifying the content name to the closest copy of the content with such a name based on the content identifier. In other words, in terms of routing, IP address of the current Internet is substituted by the content name in ICN.
- Router supports *native in-network caching*. The in-network caching may be able to ensure efficient network utilization and improve content availability.
- With *content-based security* [3] (i.e., protection and trust travel with the content, e.g., the content includes a digital signature of its publisher) or *self-certifying name* [6] (i.e., using the cryptographic digest of the content as its name), the user and even the router can examine an integrity of content.

[1] For the purpose of illustration, we use CCN [3] as a basic design example.

This feature is a critical enabler for the in-network caching. From now on, we use the content-based security as the representative term.

– *Native multicast* is supported in a network level. Router manages a list of received content requests for efficient forwarding (i.e., pending interest table (PIT) in [3]). When the router receives the requested content, it forwards the content to all requesters, so realizing multicast.

The Benefits of Employing P2P on ICN

Now, we discuss how the P2P looks like over ICN by examining potential implications of ICN features on the challenging issues of current P2P content distribution. *User-driven dynamics of user participation*, or *churn* (i.e., user's unexpected join and leave) [9] is one of the major obstacles for building stable P2P system, since it degrades P2P system performance by making content source unstable. This problem can be mitigated by the name-based routing and the in-network caching. ICN router routes the content request to the copy of content as long as the content exists. The cached contents at ICN router may improve the content availability.

Most P2P applications are network-oblivious and thus build an *underlying topology-unaware overlay network*. Network-oblivious user matching results in extensive inter-domain traffic, causing expensive operational cost to the network operators [10]. Furthermore, to reduce the inter-domain P2P traffic, the network operators often utilize various traffic shaping devices that can degrade P2P networking performance. The issues caused by the network-obliviousness can be solved by the name-based routing that is network-aware.

Open and anonymous nature of P2P (i.e., no control by central authority) attracts large number of users including *malicious users* [11]. Malicious users interfere with normal content distribution (e.g., by uploading inauthentic file). This problem can be mitigated with the name-based routing and the content-based security. A user may satisfy as long as the received content is authentic regardless of content source and transfer channel. Since ICN router can check an integrity of content based on the content-based security, the inauthentic file cannot be easily distributed by the malicious users.

Open and anonymous nature also introduces another type of non-honest user, *free rider* [12]. Free riders degrade the content distribution performance by only consuming the resources without contributing any resources. To encourage the users to contribute their resources, incentive mechanisms (e.g., tit-for-tat of BitTorrent [1]) are required. Unlike other challenging issues that can be mitigated by the ICN features, the free riding problem may get worse in ICN if there is no proper incentive mechanism. In the current Internet, each user determines its communication partners based on contribution information of neighboring users. Therefore, the user usually has to upload its content to download a content from other users. On the other hand, in ICN, ICN router matches a content publisher and a content requester based on the name-based routing protocol. In other words, a user can download a content regardless of its contribution by simply specifying the content name. Then, most users may try to exploit the name-based routing while not contributing their resources, which can lead to the tragedy of digital commons. Therefore, in this paper, we propose the contribution-aware ICN to utilize the user resources efficiently in ICN by mitigating the potential free riding problem of P2P over ICN.

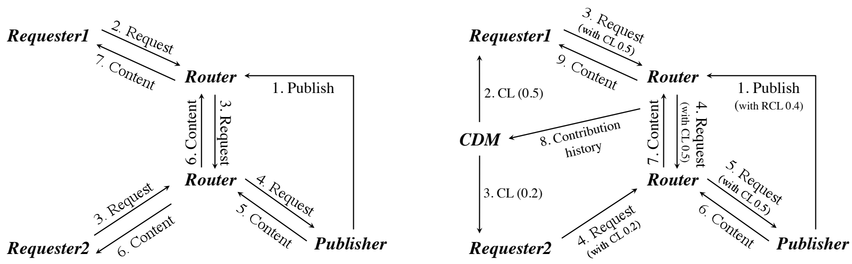
2.2 Approach

We first discuss main features of the contribution-aware ICN. Then, we will show how the contribution-aware ICN can be implemented over existing ICN architectures. Unlike current P2P applications where each user usually manages contribution information of its neighboring users and determines whom to upload, the user cannot do the same job in ICN, since a matching between a publisher and a requester is done by ICN router. Because the users cannot manage the information of other users, even existence of other users, the management of user information for incentivizing user contribution needs to be done not by the user itself but by a network side. For this purpose, we propose followings (Fig. 2(b) and Fig. 3(b)).

Management of User Contribution. We introduce one additional entity, called content distribution manger (CDM) to manage contribution history of users in terms of content distribution. The contribution history can include content name, transfer time, publisher ID, and requester ID. Here, we assume that each user has unique ID. ICN router can generate the contribution history after checking the integrity of transferred content and report it to CDM. CDM generates a contribution level (CL) for each user according to corresponding contribution history when it receives a user request for CL. CL can include target content name, CL value, expiration time, and target user ID. CL shows how much each user contributes to the content distribution. For example, CL can be calculated as a ratio of uploaded content to downloaded content. The content publisher can encourage the user contribution by manipulating CL calculation. For example, CL can be generated based on only publisher ID to foster persistent contribution incentives by recognizing and rewarding contributions made by a user across various contents and time. CDM signs CL with its private key to prevent the users from generating false CL if it needs to return CL to users. The content provider can deploy CDM for their content distribution service. Each CDM has an unique identifier so that the user request for CL can be routed to appropriate CDM based on the name-based routing. Here, we assume that the user can download a metadata file including a name of corresponding CDM through a search engine before requesting the content.

Content Publication with Required CL. Basic approach for incentivizing user-assisted content distribution is to allow a user to download a content only when the user uploads a content. For this, the content publisher specifies a required contribution level (RCL) that needs to be satisfied by the requester's CL to download the content when it publishes the content.

Contribution-Aware Routing. ICN router compares the content name and CL of the requester with the name and corresponding RCL of routing table.



(a) CCN (b) Contribution-aware ICN

Fig. 2. Contribution-aware ICN over CCN

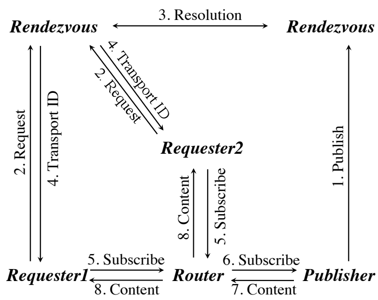
If there is matched one, it forwards the user request. If there is no matched entry in the routing table (e.g., no entry for the requested content, lower CL than RCL, or an expiration time of CL is over), ICN router drops the user request or returns an error to the requester. For this, the routing table of ICN router needs to be extended to include RCL of published content.

2.3 Implementation of Contribution-Aware ICN

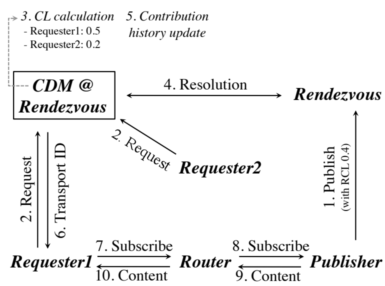
Here, we discuss how the contribution-aware ICN can be implemented over existing ICN architectures. For this purpose, we choose content centric networking (CCN) [3] and publish-subscribe internet routing paradigm (PSIRP) [5] as representative existing ICN architectures.

Contribution-Aware ICN over CCN. The main concept of CCN is to route a content request towards a location where the content has been published (Fig. 2(a)). Once an instance of content is located, it is delivered to the requester along the path the request came from. All the nodes along that path may cache the content in case they have more requests for it. The contribution-aware ICN can be implemented over CCN as follows (Fig. 2(b)). CDM can be deployed as a separate entity. When the requester wants to download a content, it first acquires its CL from CDM. CDM calculates CL of the requester according to a policy given by a content publisher and returns CL to the requester. Then, the requester issues a content request together with its CL. The content request is routed to a copy of content and the content is delivered to the requester if the requester's CL is higher than RCL of the requested content. When ICN router forwards the content to the requester, it generates the contribution history and reports it to CDM.

Contribution-aware ICN over PSIRP. In PSIRP, content is published into the network (Fig. 3(a)). Then, requesters can subscribe to the published content. The publication and the subscription are matched by a rendezvous system. The matching procedure returns a transport ID that can be used for routing of content through a forwarding network. In PSIRP, the contribution-aware ICN can



(a) PSIRP



(b) Contribution-aware ICN

Fig. 3. Contribution-aware ICN over PSIRP

be implemented as follows (Fig. 3(b)). CDM can be deployed at the rendezvous system. When a requester wants to download a content, it sends a content request to the rendezvous system. Then, the rendezvous system first calculates CL of the requester. If CL of the requester is higher than RCL of the requested content, the rendezvous system matches the requester and the publisher. After processing the user request, the rendezvous system returns a transport ID to the requester who has enough CL. The rendezvous system also updates the contribution history of the matched requester and the publisher. A connection for content forwarding is setup based on the returned transport ID and the content is delivered to the requester.

3 Contribution-Aware Content Distribution

Now, we turn our attention to an incentive mechanism to encourage the user-assisted content distribution over the contribution-aware ICN. The incentive mechanism over the contribution-aware ICN can be achieved by CL generation policy and RCL assignment policy. Two policies can be managed by one entity (i.e., a content provider or a user) or different entities (e.g., a user can publish a content with its own RCL assignment policy through public CDM that has pre-defined policy for CL generation set by a content provider). According to a content distribution policy of the publisher, various policies for CL generation and RCL assignment are possible. In this paper, we introduce our choices for a file sharing as a starting point of our research while leaving other possible approaches for future work. In this paper, we assume that RCL of original content publisher is used for re-publication of downloaded content by users. We also assume that a content is divided into segments and each segment is named together with its content name (e.g., ContentName.SegmentID). The original content publisher publishes its content with RCL incrementally increasing. For example, in case of content consisting of 300 segments, first 100 segments have 0 RCL, next 100 segments have 0.1 RCL, and remaining 100 segments have 0.2 RCL. For bootstrapping of newly joining users, some segments are published with zero RCL (i.e., no CL requirement for download). The newly joining peers need some segments to upload, since they need to increase their CL by uploading the content. By downloading and uploading the segments with 0 RCL, the newly joining user may be able to increase its CL enough to download the segments with non-zero RCL. The incrementally increasing RCL may encourage the users to keep uploading the downloaded segments to increase CL enough to satisfy RCL of remaining segments requiring higher RCL than the downloaded segments.

CDM generates CL according to a pre-defined method when it receives a request from a user. As a basic form, in this paper including the evaluation part, CL is calculated as a ratio of the uploaded content to the downloaded content. CL is valid for 10 seconds. Due to some reasons, a user may do not have chance to upload its content even though they willingly want to contribute their resources. In this case, CDM generates *free pass* CL (FPCL) that can be used to download some segments without satisfying RCL. For example, when there is only one requester or when other users already have segments that the requester has, the requester cannot upload to anybody. When only one requester exists, FPCL for all segments is generated. When the requester does not have segments to upload, FPCL for rare segments is generated so that the requester can have a chance to upload the downloaded rare segments. To prevent the free riders from receiving FPCL from CDM, CDM generates FPCL only for users who publish every downloaded segment under an assumption that the user who publishes the content willingly uploads the content when it receives the content request. For this, in CCN case, the router needs to report the content publication by users to CDM. Please note that CDM can know when what user downloads what content based on the contribution history.

4 Evaluation

Using ns-2 [13], we evaluate (1) an effect of user participation on content download performance in ICN and (2) a feasibility of the contribution-aware ICN and the incentive mechanism in terms of resources utilization efficiency. We use PSIRP architecture as the existing ICN architecture for our simulation. We build the simulation topology by using transit-stub model. Our topology includes 1 transit and 10 stub networks connected to the transit domain. In our simulation, a performance bottleneck is user link capacity. For link capacity of users, we set 120KB/s and 40KB/s for downlink and uplink capacity. We use 1,000 users including one initial content publisher. 100MB-sized content is divided into 400 256KB-sized segments. To study an effect of different user types in terms of participation in the content distribution, we divide users into three types: free rider (no content upload), altruistic user (upload the downloaded segments regardless of its CL), and rational user (upload the downloaded segments to increase its CL just enough to download remaining segments). In addition, to study an effect of RCL assignment policy, we assign increasing RCL (0, 0.1, 0.2, and 0.3 for each 100 segments) or flat RCL (0 for 100 segments and 0.1 for remaining 300 segments) for the content. For comparison purpose, we conduct simulations with the existing ICN and the contribution-aware ICN. In the existing ICN, every

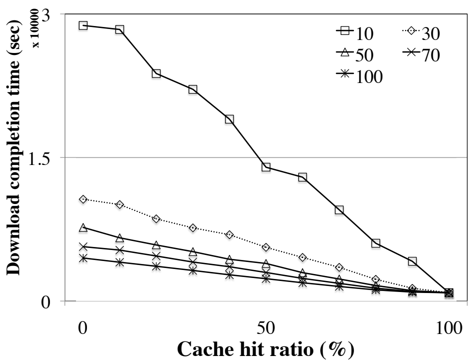
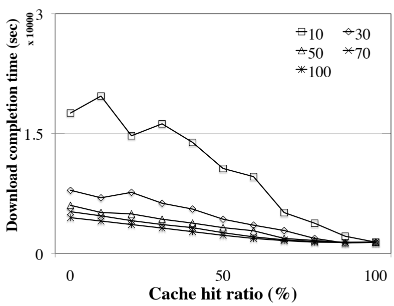
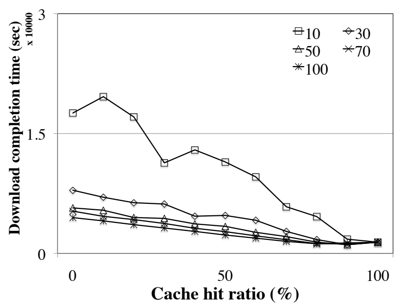


Fig. 4. Existing ICN without RCL



(a) Increasing RCL



(b) Flat RCL

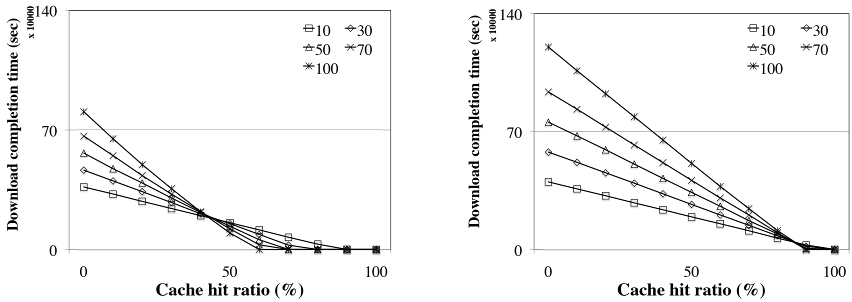
Fig. 5. Contribution-aware ICN with altruistic users

user downloads the content regardless of its contribution, since there is no RCL. On the other hand, in the contribution-aware ICN, only user who satisfies RCL can download a content.

4.1 Effect of User Participation

Through simulations, we find that the user participation has noticeable effect on download performance in ICN (including the existing ICN and the contribution-aware ICN). In the existing ICN (Fig. 4) and the contribution-aware ICN (Fig. 5)[2], the download performance improves linearly as the cache hit ratio increases. On the other hand, the download performance improves significantly as a number of altruistic users increases. Even though the free riders download the content without corresponding contributions in the existing ICN,

[2] In the figures, numbers of figure legend indicate % of non-free riders among 1000 users. In the existing ICN, the non-free riders are altruistic users, since there is no RCL.



(a) Increasing RCL

(b) Flat RCL

Fig. 6. Contribution-aware ICN with rational users

more number of altruistic users leads to better performance by providing more upload capacity. Due to the same reason (except that the free riders can only download the segments with 0 RCL), in the contribution-aware ICN, the download performance improves as a number of altruistic users increases. This result shows that the user participation has significant impact on the content distribution performance, especially when the cache hit ratio is low. This also means that the download performance can be improved through the user participation even though the content is not popular enough to be cached by ICN router.

We have interesting observations from the contribution-aware ICN with rational users (Fig. 6(a)). When the cache hit ratio is low (less than 40% in our simulation), more number of rational users leads to worse content distribution performance. In case of the free riders, they cannot download segments with non-zeo RCL while freely downloading the segments with 0 RCL. On the other hand, the rational users can continue to download the segments as long as they have enough CL. However, the rational users stop their contributions when they have enough CL to download the segments with non-zero RCL. In other words, amount of upload capacity provided by the rational users is not guaranteed while total amount of required download capacity is fixed. Due to a shortage of upload capacity, some content requests of rational users who have enough CL cannot be handled rapidly and thus this leads to poor performance. However, if the cache hit ratio is high enough to complement the shortage of upload capacity, more number of rational users leads to better performance.

4.2 Effect of RCL

From the comparison between the existing ICN (Fig. 4) and the contribution-aware ICN with the altruistic users (Fig. 5), we find that the free riders degrade the content distribution performance by consuming system resources (i.e., upload capacity of publisher and non-free riders) without contribution. Please note that a comparison between the existing ICN and the contribution-aware ICN with rational users is meaningless, since the non-free riders in the existing ICN

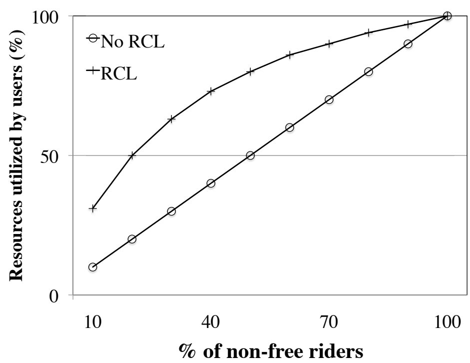


Fig. 7. % of resources utilized by non-free riders

are the altruistic users. In the existing ICN, the free riders and the non-free riders show similar download performance, since they download the content regardless of their upload contributions. This result shows that there should be proper incentive mechanism to prevent the free riders from exploiting the system resources for efficient utilization of system resources in ICN.

In the existing ICN, the portion of system resources utilized by the non-free riders increases linearly as a number of the non-free riders increases, since the free riders and the non-free riders compete with each other to download the content regardless of their contributions. On the other hand, in the contribution-aware ICN (regardless of types of non-free riders), more portion of system resources is utilized by the non-free riders (Fig. 7). Remaining portion of the system resources are used by the free riders to download the segments with zero RCL. Thus, that portion decreases as a number of non-free riders increases. Even though the download performance of contribution-aware ICN with rational users is not as good as the case of the contribution-aware ICN with altruistic users due to the unwillingness of user participation in content distribution, most portion of the system resources is utilized by the non-free riders. Above results show that the contribution-aware ICN can utilize the system resources efficiently by preventing the free riders based on the contribution-related information (i.e., RCL, CL, and contribution-aware routing). It also means that the download performance of the contribution-aware ICN can be further improved with a proper incentive mechanism (i.e., RCL assignment and CL calculation policy). We will study this later as future work.

Now, we examine an effect of two RCL assignment policies on the download performance: increasing RCL and flat RCL. The contribution-aware ICN with altruistic users show similar download performance with both the increasing RCL (Fig. 5(a)) and the flat RCL (Fig. 5(b)), since the altruistic users continue to contribute regardless of their CL. On the other hand, in case of the contribution-aware ICN with rational users, the increasing RCL (Fig. 6(a)) is more effective than the flat RCL (Fig. 6(b)) to encourage the rational users to contribute their resources. This result shows that the increasing RCL can encourage the rational users to keep uploading the downloaded segments to increase CL enough to satisfy RCL of remaining segments.

5 Conclusion

In this paper, we introduce the contribution-aware ICN to utilize the user resources for efficient content distribution by mitigating the free-riding issue. The contribution-aware ICN utilizes the centralized entity to manage the user contribution and the content is published with the required contribution level so that the users with enough contribution only can request the content. Through simulation, we show that the contribution-aware ICN encourages the users to contribute their resources. We also show that the content download performance improves significantly as the number of users contributing the resources increases. We are currently focusing on efficient utilization of given user resources and effective incentive mechanism when there are various types of users publishing content with different RCL.

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