Incentive Cooperative Caching for Localized Information-Centric Networks

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***Abstract*—In-network caching has the potential to improve network efficiency and content distribution performance by satisfying user requests with cached content in Information-Centric Networking (ICN). Due to the fact that users in the same network domain can easily share their cached content with each other via home network devices, to reduce the transmission cost for obtaining content from the core network, caching cooperation home networks are constructed. Derived from the analysis of the economic relations among ICN entities, we propose an efficient incentive cooperative caching mechanism for content retrieval in localized ICNs in this paper. Particularly, access networks give rebates to those users who provide locally cached content for content retrieval in cache cooperation. To minimize the cost (including rebate and transmission cost) of obtaining a piece of content in the proposed caching framework, we also formulate an optimal caching problem as a multiple-choice knapsack problem. Furthermore, a sub-optimal caching scheme is proposed to handle the optimal content placement problem efficiently. Simulation results verify the superiority and efficiency of the proposed sub-optimal caching scheme compared with random caching.**

***Index Terms*—Information-Centric Networking (ICN), incentive mechanism, cooperative cache, economic model**

I. Introduction

Information-Centric Networking (ICN) [1] has been proposed to address the mismatch between the current IP-based networks' host-centric principle (supporting communications between any pair of end-hosts identified with an IP address) and today's content-oriented services (focusing on the content itself rather than the IP address of content source). In this paper, we use the abbreviations CCN/NDN to refer to the main architecture proposed in [2] for ICN. In ICN, each information item is uniquely identified and authenticated without being associated with a specific host. A distinctive feature of this paradigm is that it enables in-network caching, namely, intermediate nodes can cache passing-by contents so as to satisfy subsequent requests with the cached copies.

Research has recently focused on optimizing the performance of core network caching to improve the efficiency and reduce the transmission delay [3]. However, few research works explore the caching possibility and capabilities of the user devices. In fact, with the development of technology, network data can now be stored at many edge devices [4], [5], including some home network access points (e.g., home routers). A general trend is that users' home routers are equipped with a large storage and are capable of caching items. Lee and Nakao [6] first propose the concept of *"user-assisted in-network caching"*, in which users in the same network domain can achieve the attractive features of in-network caching by sharing downloaded content with each other. Sourlas et al. [7] propose an information-resilience mechanism through user-assisted caching in CCN/NDN for the content retrieval in disruptive, fragmented network cases. However, both [6] and [7] do not consider the actual deployment of the user-assisted caching in an ICN-based architecture.

In IP-based networks, a user downloads a piece of content directly from a Content Provider's (CP) server over an access network and a core network, where the core network primarily provides transmission services between CPs and access networks. To reduce the transmission cost charged by the core network operator, CPs can buy the storage capacity of edge storage facility (i.e., Content Distribution Networks (CDNs)) [8] and place popular content at the access networks. However, in an ICN-based architecture, without an entity like CDNs that play the transaction brokerage role between CPs and different networks [9], CPs would have to establish content delivery relationships with multiple networks. This leads to the fact that CPs are not willing to cooperate in the process of economic incentives without getting enough revenue. Besides, Rajahalme et al. [10] showed that the top-level transmission providers usually lack incentives to deploy ICN architectures, because it will take their transmission revenues away. Nevertheless, access networks usually charge users for fixed network fee. Then the transmission cost should be paid directly by access networks to the core network. With these prerequisites, we can draw the conclusion that the access network would like to utilize the end users' cache resource to decrease the traffic from the core network in an ICN-based architecture.

Motivated by the above discussion, we construct a cooperative caching framework for content retrieval in localized ICNs. In other words, we not only propose to utilize the home router as caching device to reduce the response time, but also derive an enlightening advice for the actual deployment of cooperative framework to make users available to retrieve content from other users' home routers. To the best of our knowledge, this is the first attempt to consider the ICN economic model into cooperative caching. The main contributions of this paper can be summarized as follows:

- We analyze economic relations among ICN entities. From the perspective of content retrieval in localized ICNs, an efficient incentive cooperative caching mechanism

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is proposed. Particularly, access networks give rebates to the users who provide locally cached content for content retrieval in caching cooperation, which reduces the transmission cost for obtaining content from the core network.
- In order to minimize the cost (including rebate and transmission cost) of obtaining a piece of content for access network in the proposed cooperative caching framework, an optimal caching problem is formulated as a multiple-choice knapsack problem. Since the problem is NP-hard, a sub-optimal caching scheme is also proposed to solve the optimal caching problem efficiently.
- We obtain some valuable insights on the impacts of different parameters on the content obtaining cost. The superiority of the sub-optimal caching scheme is verified via the simulation compared with the random caching scheme.

The rest of the paper is organized as follows. Section II presents the background. Then we describe our proposed cooperative caching mechanism in Section III, and we further formulate the cooperative caching problem in Section IV. Numerical evaluation results are shown in Section V. At last, the conclusion is drawn in Section VI.

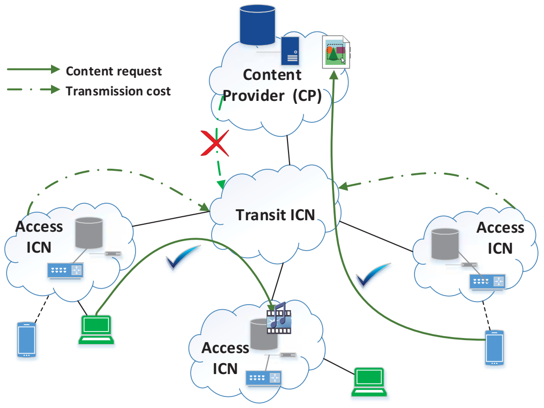


Fig. 1: ICN communication model: Different from the current network where users request contents from CP, users in ICN just look for content regardless of the place that is located. Unlike the current network where the CP is charged for the cost of content transmission, the CP in ICN is not willing to undertake the transmission cost.

II. Background

The rapid increase of content delivery on the Internet has revealed the need for a new networking paradigm. As Fig. 1 shows, the emerging trend is that users do not care about where the content is located or how it is delivered, but only focus on the information (content). Corresponding architectural proposals are generally referring to Information-Centric Networking (ICN) [1], which gives a new communication paradigm to increase the efficiency of the content obtaining.

Unlike the current TCP/IP model where caching is usually deployed as an application layer overlay, ICN makes caching be integrated into the network layer, named as in-network caching. In the current content delivery ecosystem, Content Distribution Networks (CDNs) provide both the content delivery and the transaction brokerage functionality. In this situation, CP only needs to care about paying for content delivery. Thus, in an ICN-based architecture, in the absence of an entity that plays the transaction brokerage role between CP and different networks [9], CP would have to establish content delivery relationships among multiple networks, which will reduce their willingness to pay for caching services and the viability of paid content delivery.

Hajimirsadeghi et al. [11] proposed a pricing model to establish an economic incentive mechanism for caching and sharing content in ICN which consists of access ICNs, a transit ICN and a content provider. As shown in Fig. 1, Access ICNs can gain revenue from end users that they serve and pay for the traffic generated by their users to the connected Transit ICN. The fee depends on the line capacity or the upstream and downstream direction traffic. Access ICN thus has the intention to decrease the flow from each terminal to Transit ICN so that the investment required and traffic cost for each user could be reduced. Actually, this can be realized by deploying caching in edge networks where such significant realizable benefits from caching exist. In this case, the access network can cache content for cost savings and thus obtain performance improvement on its network.

III. Incentive Cooperative Caching Mechanism

In this section, we give an enlightening advice for the actual deployment of cooperative caching in residential community networks. Furthermore, an ICN-based incentive mechanism is proposed to motivate users to join the cache cooperation.

A. Overview

A residential community network architecture is composed of individual home networks and an arbitrary number of consumers who obtain multimedia resources through their own home routers. These home routers are capable of caching contents.

In this paper, a central gateway is introduced into the community network to manage the home routers. The primary function of the central gateway is to redirect the user's requests to the home routers which cache the requested contents, so as to achieve the cache cooperation within the community. To motivate users to join the cache cooperation, Access ICNs give rebates to those users who provide locally cached content for content retrieval in the cooperation processes. We will explain the details of the mechanism in the following subsections.

It should be noted that the central gateway can be deployed and managed by the Access ICNs. In addition, in this paper, we focus on the cooperative caching among home routers. We don't discuss the caching function of the central gateway and leave it for future research.

B. A Community Cooperative Caching Framework

To achieve caching cooperation in a residential community, users' requests should be able to be redirected to other users' home routers for content retrieval. As Fig. 2 shows, a central gateway is introduced to play the role as a centralized controller. Stemming from the named-based routing in ICN, users who are interested in the same content can easily cooperate with each other for content distribution without specific protocols or applications. All we need to do is to extend a Trace Table in the central gateway. The functionality of other components, namely the Content Store (CS), the Pending Interest Table (PIT) and the Forwarding Information Base (FIB) remain the same as in the original NDN content router design presented in [2]. Also, it almost keeps users' home routers unchanged, making the entire design a lightweight task.

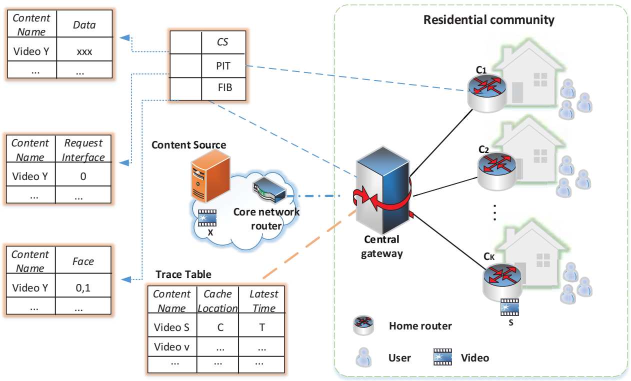


Fig. 2: Residential community networks architecture with a cooperative caching framework.

In the proposed caching framework, the central gateway determines the caching location of content, according to the request distribution. After receiving a piece of content, the central gateway marks the content and delivers it to the corresponding home routers. Meanwhile, the Trace Table, maintained by the central gateway, records each content cached in all home routers. Each trace is a 3-tuple entry $(ContentName, CacheLocation, LatestTime)$ which denotes the name of the cached content, the cache location and the most recent time that the trace is referred to, respectively.

The content delivery procedure can be described as follows: after a content request is launched by a user, it first searches the CS in the local home router, which processes the packet in the same way as in NDN [2]. Particularly, if a matching item is found in the CS, the router sends the item to the face which the request arrives on and discards it (since it is satisfied). Otherwise, the request will be forwarded to the central gateway which looks up the request in the Trace Table. If a piece of content is hit, which indicates the neighboring home router has the object, the request will be redirected to the corresponding home router and the requested object will be retrieved back. If the search of the residential community also fails, the object will be retrieved from the content source (i.e., a cached node in ICN, Content Provider) according to FIB.

C. An ICN-based Economic Incentive Mechanism

To motivate users to join the cache cooperation, we propose an incentive mechanism. In this mechanism, Access ICNs give rebates to the users who provide the locally cached content for cooperative content access, and the rebates are regarded as a portion of the Access ICNs' overall cost. As shown in Fig. 3, we consider the transmission cost C_t when a piece of content is transmitted from a content source through Transit ICN. Meanwhile, C_r ($C_r < C_t$) corresponds to the rebate paid by the Access ICNs to the users when their home routers provide a locally cached item to others. Both C_r and C_t are considered into the cost of obtaining a piece of content. However, if the content is found in the local router, no cost will be generated.

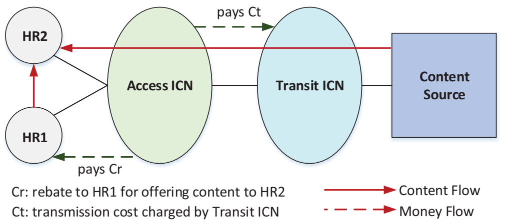


Fig. 3: An ICN-based economic incentive mechanism.

It should be noted that C_r or C_t does not represent the content price of a piece of content. Users pay the content price directly to the content publisher through an out-of-band secure payment system. A digitally signed rebate framework [12] needs to be supported so that the rebate recipients can electronically validate and redeem the rebate with the Access ICN. Operationally, the paraments C_t and C_r are set by ICN operators based on their operating cost. Hence, the users are unable to control those parameters.

To minimize the cost for Access ICNs, an optimal content caching scheme is needed for C_r and C_t. Formulation and analysis of the optimal caching problem are presented in the next section.

IV. Problem Formulation and Analysis

In this section, we formulate an optimization problem for the incentive cooperative caching network. Furthermore, a sub-optimal caching scheme is proposed to solve the problem efficiently.

A. Content Obtaining Cost Formulation

We assume that the statistical popularity of the content can be modeled as the $Zipf$ distribution in this paper. Denote $\mathcal{N}$ as a collection of contents, with total number N=$|\mathcal{N}|$. The higher the ranking of a piece of content, the larger the accessed probability of it. According to $Zipf$ law, the popularity of the i-th popular content is given by

$$f_i = \frac{1/i^r}{\sum\limits_{m=1}^{N} 1/m^r}, \quad (1)$$

where the parameter r $(0 < r)$ is a $Zipf$ parameter, which determines the skewness in a request pattern.

To establish an accurate mathematical model, we first define a content set variables X_i^j is either 1 or 0. If $X_i^j = 1$, $j = 1, ..., K$, $i = 1, ..., N$, it means the i-th ranked content is cached in j-th home router; otherwise it is not. In addition, we define f_i^j as the probability of requesting the i-th ranked content in j-th home router and the entire popularity of the i-th ranked item in the whole community is $f_i = \sum_{j=1}^{j=K} f_i^j,\ j = 1, ..., K$.

We assume that not all home routers have the storage capacity. This assumption is reasonable due to the following facts: i) there exist different types of home routers; ii) some users refuse to cooperate with others. Thus, we define the caching availability of the users' home routers with ω_j, $j = 1, ..., K$. If the j-th home router has the storage capacity S_c, then $\omega_j = 1$; otherwise, $\omega_j = 0$. Then the average cache-able probability of home routers is

$$\omega = \frac{1}{K}\sum_{j=1}^{j=K} \omega_j,\ j = 1, ..., K. \tag{2}$$

Each piece of content is considered has the same size in this paper. To optimize the local hit rate of a home router, users' requests need to be satisfied locally as much as possible. In this case, the purpose is

$$\begin{aligned} \textbf{Max} \quad & \sum_{j=1}^{K}\sum_{i=1}^{N} \omega_j X_i^j f_i^j, \\ \textbf{s.t} \quad & \sum_{i=1}^{N} X_i^j \le S_c, \forall\ j \in \{1, ..., K\}, \end{aligned} \tag{3}$$

where the constraint is used to make sure the total size of caching contents in each home router do not exceed its caching capacity S_c. For this objective function, the optimal caching strategy is all home routers cache the most popular contents. However, this leads to noncooperation and can result in serious content duplication. Also, for those requests that cannot be satisfied locally, desired contents will be transmitted from the remote content source, yielding high content transmission cost.

On the contrary, to increase the probability of obtaining a piece of content of a residential community, diversity of contents needs to be guaranteed. In this case, the purpose is

$$\begin{aligned} \textbf{Max} \quad & \sum_{j=1}^{K}\sum_{i=1}^{N} \omega_j X_i^j f_i^j \ + \sum_{j=1}^{K}\sum_{i=1}^{N} \omega_j (Y_i - X_i^j) f_i^j, \\ \textbf{s.t} \quad & \sum_{i=1}^{N} X_i^j \le S_c, \forall\ j \in \{1, ..., K\}, \end{aligned} \tag{4}$$

where Y_i is either 1 or 0. $Y_i = 1$ means the i-th ranked content is cached in one of the home routers; otherwise it is not. The optimal cache strategy in this case is a full cooperation, which means all home routers would try to cache the unique content within the residential community, namely $\sum_{i=1}^{N} X_i^j \le 1, \forall\ j \in \{1, ..., K\}$. However, this may cause the home router to cache some items with low popularity, and users rarely access them.

To quantify the effect of the different content obtaining procedures, $H_{i,j}^L$ is defined as the probability that j-th user obtains the i-th ranked content from CS in its own home router, namely the local hit rate. $H_{i,j}^R$ denotes the probability that a requested content is obtained from neighboring routers in the residential community after the local search fails. Likewise, $H_{i,j}^T$ represents the probability that a requested content is hit outside of the residential community. Hence, we have

$$H_{i,j}^L + H_{i,j}^R + H_{i,j}^T = 1, \tag{5}$$

which means a piece of content can always be delivered to the users.

In accordance with our economic incentive mechanism, the obtaining cost for i-th ranked content is zero if it is found locally, C_r when it is found in any other home router in the residential community, and C_t when it is delivered from the outside of the community. To minimize the i-th ranked content obtaining cost we can get

$$\begin{aligned} \textbf{Min} \quad & C = \ H_{i,j}^R C_r \ + \ H_{i,j}^T C_t, \\ \textbf{s.t} \quad & \sum_{i=1}^{N} X_i^j \le S_c, \forall\ j \in \{1, ..., K\}, \end{aligned} \tag{6}$$

where $H_{i,j}^R = \sum_{j=1}^{K}\sum_{i=1}^{N} \omega_j (Y_i - X_i^j) f_i^j$, $H_{i,j}^T = \sum_{j=1}^{K}\sum_{i=1}^{N} \omega_j (1 - Y_i) f_i^j$. This optimal problem is a typical $0/1$ multiple-choice knapsack NP-hard problem [5]. Especially, when where are a big scale content set and a large number of home routers, it is difficult to get the best cache content placement scheme.

B. A Sub-optimal Caching Scheme

The aforementioned optimal solution of minimizing the content obtaining cost is complicated and time-consuming. Thus, we relax the mathematical model and the constraint condition to come up with a general solution to solve the problem efficiently. The caching availability ω_j is considered as statistically identical and then it is equal to the average cache-able probability ω described in (2). Then the local hit rate H^L is

$$H^L = \frac{1}{K}\sum_{j=1}^{K}\sum_{i=1}^{N} H_{j,i}^L f_i = \frac{S_c \omega}{K S_c \omega}\sum_{i=1}^{N} n_i f_i = \frac{1}{K}\sum_{i=1}^{N} n_i f_i, \tag{7}$$

where n_i represents the total number of the copies of the i-th ranked content cached in all home routers. $K S_c \omega$ represents the total caching capacity of the home routers.

Let M represent the set of all cached contents in a community. The probability of finding the i-th ranked content in the community is $\sum_{i \in M} f_i$, and the hit rate of the content which is not cached in one home router is $H^R = \sum_{i \in M} f_i - H^L$.

Referring to the properties of the optimal object placement in [13], we propose the following partition caching scheme.

- Firstly, it should be mentioned that in the proposed caching framework, the caching location of content is determined by the central gateway, according to the accounted request distribution.
- Secondly, cache space of each home router is divided into a duplicate part and a unique part. The parameter η indicates the fraction of the cache that is utilized to store duplicate contents. For the duplicate part, the cached contents are full-duplication, while for the unique part the cached contents are single.
- Furthermore, the contents with high popularity are cached in the home routers in advance, one by one without any

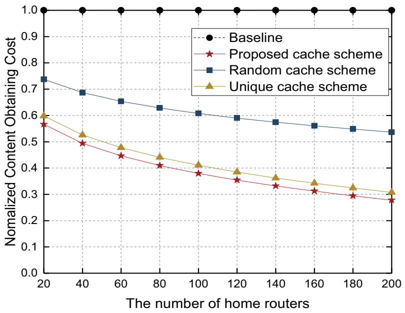


Fig. 4: Content obtaining cost of different cache schemes.

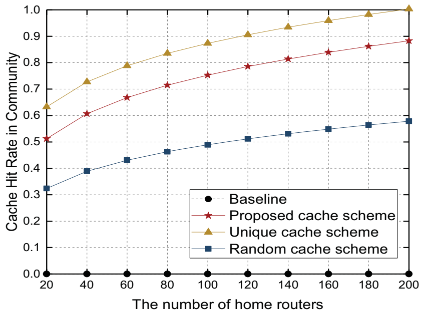


Fig. 5: Hit rate in community of different cache schemes

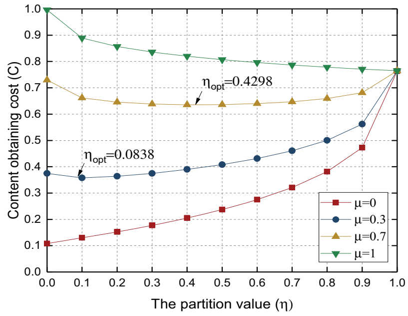


Fig. 6: Impact of η and u on content obtaining cost

identity interval. Also, the most popular content in the unique part is less popular than the least popular content in the duplicate part.

For simplicity, we assume each user has the same request frequency and request mode in statistics, namely, $f_i^o = f_i^q$, $\forall o, q \in \{1, 2, ..., K\}, o \neq q$. Therefore, as in [13], the probability of finding a piece of content from the t most popular content cached by the home routers can be express as

$$f(t) \triangleq \sum_{i=1}^{t} f_i \approx \int_1^t \frac{\frac{1}{i^r}}{\sum\limits_{m=1}^{N} \frac{1}{m^r}} d_i = \frac{\int_1^t \frac{1}{i^r} d_i}{\int_1^N \frac{1}{m^r} d_m} = \frac{t^{1-r} - 1}{N^{1-r} - 1}. \tag{8}$$

According to the proposed scheme, we can rewrite H^L as

$$H^L = f(\eta S_c)\omega + \frac{f(\eta + \omega K(1-\eta)S_c) - f(\eta S_c)\omega}{\omega K}, \tag{9}$$

where ω is the local cache-able probability, and the first item in the above equation (9) represents the probability that a piece of content can be found in the local duplicate part. $S_c(1-\eta)K\omega$ represents the storage capacity of all the unique parts. Thus the second item in the above equation (9) represents the probability that a piece of content can be found in the local unique part. Similarly, we have

$$H^R = \frac{(\omega K - 1)\left[f(\eta + \omega K(1-\eta)S_c) - f(\eta S_c)\omega\right]}{\omega K}. \tag{10}$$

Meanwhile, H^T can be expressed as $H^T = 1 - H^L - H^R$. Substituting H^R and H^T in (6), the objective can be rewritten as

$$C = \left[1 - H^R(1-\mu) - H^L\right] C_t, \tag{11}$$

where μ is C_r/C_t. We can compute the optimal value of η by $\frac{\partial C}{\partial \eta} = 0$, yielding the minimum content obtaining cost C.

V. Numerical Results

In this section, we examine the performance of the proposed cooperative caching scheme, in comparison with the random caching scheme and the unique caching scheme. In the random caching scheme the contents are randomly cached in the home routers. The unique caching scheme corresponds to the case of maximum content categories. All of them are based on the caching cooperation. Meanwhile, the non-caching is included as the performance benchmark. In the simulation, the typical values of the system parameters are listed in Table I. If not specified, ω is set to 1, which means all the home routers have the cache capacity S_c and join the cache cooperation.

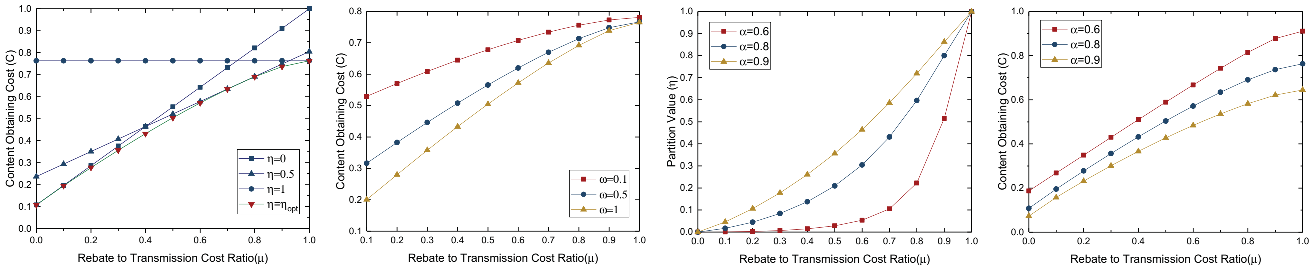
TABLE I: Numerical Calculation Parameter Settings

Parameters	Value
Storage capacity of one home router: S_c	300 Gbits
The number of the contents: N	100000
The number of the home routers: K	200
The size of one content: S	1 Gbits
Rebate-to-download-cost ratio: μ	0.2
The average cache-able probability: ω	1
Zipf constant: r	0.8

The content obtaining cost with respect to the number of home routers in the community is presented in Fig. 4. For the non-caching scheme (termed as a baseline in the figure), the cost of obtaining one piece of content from the core network is normalized to one. The content obtaining cost of other caching schemes is normalized by the baseline scheme. It can be seen from the figure that with the increase of the home router numbers, all schemes result in a declining trend, since more content will be obtained within the community. Compared with the unique caching scheme and random caching scheme, the proposed caching scheme has 9% and 24% cost saving, respectively.

According to (5), the cache hit rate of different cache schemes in a community can be obtained in the simulation, as shown in Fig. 5. It can be seen that the hit rate of the unique caching scheme is a bit higher than the proposed scheme. That is because unique caching scheme ensures the maximum of content categories in a community. In this situation, some of the cached items with low popularity are rarely requested by users. We observe from the figure that the caching hit rate of the proposed suboptimal caching scheme is increased by 36% compared with the random scheme. Fig. 6 depicts the impact of the partition value η on the content obtaining cost. As we can see, there always exists an optimal partition value which minimizes the cost of obtaining content for different rebates. Along with the growth of rebate ratio (i.e., $\mu = 0,\ 0.3,\ 0.7,\ 1$), caching more popular contents in duplicate area can minimize content obtaining cost and result in a larger optimal partition value η_{opt} (i.e., $\eta_{opt} = 0,\ 0.0838,\ 0.4298,\ 1$).

Different cost performance is compared for four partition value η (i.e., $\eta = 0,\ 0.5,\ 1,\ \eta_{opt}$), as shown in Fig. 7(a). $\eta = 0$ leads to near-best performance for small μ values,



(a) (b) (c) (d)

Fig. 7: (a) Comparative minimum cost. (b) Impact of total cache capacity on cost. (c) Optimal value of η for α. (d) Minimum cost for α.

since for small μ, the cost relies mainly on H^T. When μ is large (i.e., u>0.8), $\eta = 1$ acquires near-best performance. This is because, for large μ, the cost depends mainly on H^R, which is maximized when $\mu = 1$. With the proposed caching scheme in this paper and via the η_{opt} values, we can always achieve the minimum obtaining cost for different μ. Fig. 7(b) illustrates how the total cache capacity impacts the obtaining cost when $\eta = \eta_{opt}$. By increasing μ, the cost of obtaining content in a community increases, and therefore the overall content obtaining cost also increases. With the increase of total cache capacity, more content can be cached and cooperative transmission can be promoted.

Fig. 7(c) depicts the value of η_{opt} for three different values of the $Zipf$ parameter r. For high μ (i.e, when the rebates given to the users is high), routers will be set higher η to cache more popular contents locally. For small μ (i.e, when the rebate for obtaining a content from other home routers is negligible), the transmission cost can be minimized by choosing small η to store a higher number of different content in the community. We can also find that optimal η grows slowly for small r. since the percentage of requests for popular contents is not enough to reduce the transmission cost. Fig 7(d) demonstrates the corresponding minimum content obtaining cost when all participant home routers in the community with the proposed cache scheme with optimal η. With a higher r, more requests satisfied from the local cache results in a lower obtaining cost.

VI. Conclusion

This paper develops an efficient caching cooperation for the content retrieval in localized ICNs. To reduce the cost for obtaining content from the core network, an incentive mechanism by giving rebates from Access ICNs is proposed to motivate users to join the cooperation. An optimal caching problem is formulated to minimize the cost of obtaining a piece of content. Furthermore, a sub-optimal caching scheme is proposed to solve the optimal problem efficiently. Numerical results show that for lower rebates, the content obtaining cost can be reduced largely if higher numbers of cooperative routers adhere to the proposed caching scheme. Compared with the random caching scheme, the proposed caching scheme has significant performance gain in terms of the cost saving. Ongoing work on this topic is to consider the actual implementation and the impact of the malicious users who might modify the contents stored in their routers.

Acknowledgement

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