

# In-Network Caching for Paid Contents in Content Centric Networking

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**Abstract**—Caching is the key feature of Content Centric Networking (CCN) that allows the Internet Service Provider (ISP) to reduce network traffic crossing its network, and save bandwidth usage cost. On the other hand, it is also on benefit of the Content Providers (CPs) to cache the contents within the ISP network near the consumers. However, caching paid contents (the contents that only paying consumers can access), which are the main source of income for CP, in the ISP network complicates the CP's task of controlling content access and payment. Thus, ISP manages content placement inside its cache-enabled routers and serves content based on user demands, without any coordination with CP. There is no profit sharing mechanism between both ISP and CPs. Therefore, a payment mechanism between ISP and CPs that considers paid content caching and distribution inside the ISP network is needed. To address this challenge, we propose a new incentive mechanism for paid content caching that satisfies both ISP and CPs through the use of reverse auction. The ISP monetizes its cache storage through caching contents from multiple CPs and selling them to its customers. The reverse auction helps the ISP to get prices from multiple CPs, and to select the price that minimize its total payment. The simulation results show that our proposal satisfies all network players involved in in-network caching through increasing their utilities.

## 1. Introduction

Since last decade, many research projects have focused on proposing new Future Internet (FI) architectures that revise the model of network communication. Content Centric Networking (CCN) is one of these architectures in which content name is considered as the center of communication, where content is retrieved by name [1]. Therefore, CCN architecture implementation needs to be motivated in order to attract public attention (consumers, providers, etc.) [2].

*This work was supported by Institute for Information & communications Technology Promotion(IITP) grant funded by the Korea government(MSIT) (R0126-16-1009, Development of Smart Mediator for Mashup Service and Information Sharing among ICBMS Platform) \*Dr. CS Hong is the corresponding author.*

In CCN, nodes available in transmission path store the contents in their caches. Based on consumer requests, the contents from the cache can be returned to the consumers, rather than forwarding requests to the CP server, which may be far from the consumers. Therefore, caching does not only reduce the network traffic crossing ISP network, but also improve the Quality of Service (QoS) for the customers of both ISP and CPs, where delay is reduced when the content is retrieved from caches available in the transmission path.

In this paper, we focus on caching for paid content, where paid content refers to the category of digital content, such as text, graphics, audio, video. The paid contents are shared and distributed based on payment through the Internet [3]. The paid content is also sometimes called pay-for-content, and it has become a major revenue model for CP (e.g. YouTube [4]), where CP attracts consumers by providing them high quality of contents and charge them subscription or downloading fees.

Even though caching the paid content in the ISP network improves Quality of Service (QoS) of both ISPs and CPs, in which their customers can retrieve the content with reduced delay, it affects the CP's profit in the following ways:

- First, by delegating paid content to ISP caching, CPs do not have control over their contents for monitoring content access and payments. Instead, the ISP manages content placement inside its network based on user demands, and without any coordination with the CPs.
- Second, there is no mechanism for sharing content access control between CPs and ISP. This results in complicating CP's task of increasing content quality and diversity.
- Third, even though CP's customers pay both Internet access fees to the ISP, and content fees to CPs, there is no profit sharing between both ISP and CPs.

In order to address the above highlighted challenges, a payment mechanism between ISP and CPs is needed in order to protect CPs from losing profits, monetize ISP cache, and maximize their profits. Therefore, in this paper, our main contributions are summarized as follows:

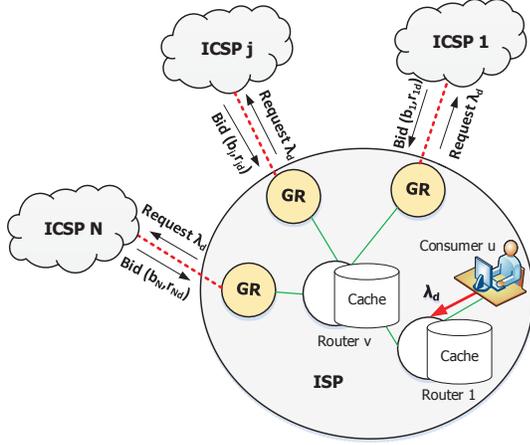


Figure 1: System Model

- We propose a new incentive mechanism for paid content caching that satisfies both ISP and CPs through the use of reverse auction model. In the proposed mechanism, ISP monetizes its cache storage through buying, caching and selling contents from multiple CPs.

As related work, in [5], the authors proposed a payment mechanism between CP and ISP through the use of non-cooperative game. The same system model was analyzed in [6], where the authors showed that there is lack of Motivation for the ISP to cache the content, thus caching causes the ISP to remunerate CP for the fraction of cached content. Another alternative has been proposed in [7], where the authors introduced Content Distribution Network (CDN) provider in the game, in addition to ISP and CP. The CP chooses CDN provider for content caching and distribution. On the other side, the CDN provider signed a fixed agreement with ISPs on behalf of CP, where ISPs are equipped with cache-enabled routers that are able to cache and distribute the contents. In [8], the author analyzed the impact of introducing CCN in ISPs networks. CCN increases profits for the ISPs which have customer-to-provider links, and reduces the profits for the ISPs which do not have customer-to-provider link(s).

The differences between our proposal with the above related works are: (1) we consider that a consumer requests content without any information on where CP is located for content payment. Thus, in CCN, the source of contents keep changing, where contents may be retrieved from different cache-enabled routers located in different networks [9], (2) ISP monetizes its cache through selling cached content to its customers, and this can be an incentive for the ISP to adopt in-network caching.

The rest of the paper is organized as follows, Section 2 discusses in details our incentive mechanism for paid content. Section 3 presents our performance evaluation. Finally, we conclude the paper in Section 4.

## 2. ISP Incentive Mechanism for Paid Content

Fig. 1 shows the system model under consideration. Both ISP and CP profits are based on consumer's payments. How-

ever, as CP does not have its own network, it uses Internet and Content Service Provider (ICSP) as a content distributor for caching and distributing its content. We consider  $\mathcal{N}$  as a set of ICSPs, where the ICSPs are other ISPs which have requested contents in their networks to sell and distribute on behalf of CPs. However, content selling and distribution agreements between CP and ICSPs are out of scope of this paper.

We model ISP's network as an undirected graph  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ , in which  $\mathcal{V}$  is the set of cache-enabled routers, and  $\mathcal{E}$  is the set of links. We consider that each router  $v \in \mathcal{V}$  is associated with cache storage  $C_v$ , while each link  $l \in \mathcal{E}$  has capacity  $C_l$ . We differentiate the internal ISP links from external transit links, where we denote  $\mathcal{L} \subset \mathcal{E}$  as a set of internal ISP links (solid lines in Fig. 1), and  $\mathcal{A} \subset \mathcal{E}$  as a set of external links (dashed lines in Fig. 1). Furthermore, we consider  $\mathcal{D}$  as a set of contents, and  $\mathcal{T}$  as a set of consumers. To access content  $d \in \mathcal{D}$ , each customer  $u \in \mathcal{T}$  pays an Internet access fee  $\gamma_a$  for each link  $a \in \mathcal{A}$ , and content price  $p_d$  for content  $d \in \mathcal{D}$ .

The traffic volume of content  $d \in \mathcal{D}$  for each internal link  $a \in \mathcal{A}$ , as defined in [10], becomes:

$$\rho_a = \sum_{d: d \text{ passes } a} \lambda_d h_d, \quad (1)$$

where  $h_d$  is the cache hit ratio for the content  $d \in \mathcal{D}$  cached inside the ISP network, while  $\lambda_d$  is the demand for content  $d \in \mathcal{D}$ . Therefore, the amount of payment from consumers to ISP is:

$$\Psi(p_d) = \sum_{a \in \mathcal{A}} \gamma_a \rho_a + \sum_{d \in \mathcal{D}} p_d \lambda_d h_d, \quad (2)$$

When the content  $d \in \mathcal{D}$  is not cached inside the ISP network, the ISP floods requests  $\lambda_d$  to all transit links through the use of Gateway Routers (GRs). The traffic volume for each external link  $l \in \mathcal{L}$  is:

$$\rho_l = \sum_{d \in \mathcal{D}} \lambda_d (1 - h_d), \quad (3)$$

where  $1 - h_d$  is the cache miss ratio for the content  $d \in \mathcal{D}$ , which is not cached inside the ISP network.

The amount  $\Phi(p_d)$  that the ISP has to pay to ICSPs for transit traffic  $\sum_{l \in \mathcal{L}} \gamma_l \rho_l$  and for getting contents  $\sum_{d \in \mathcal{D}} p_d \lambda_d (1 - h_d)$  is defined as follows:

$$\Phi(p_d) = \sum_{l \in \mathcal{L}} \gamma_l \rho_l + \sum_{d \in \mathcal{D}} p_d \lambda_d (1 - h_d), \quad (4)$$

where  $\gamma_l$  is Internet transit fee per unit of data for link  $l \in \mathcal{L}$ .

The ISP's utility depends on: (1) payment  $\Psi(p_d)$  that the ISP receives from customers through serving contents cached inside its network, and for access bandwidth, (2) payment that the ISP needs to pay to ICSPs for transit bandwidth, and for caching contents, and (3) the cost of cache deployment. Thus, the ISP's utility is expressed as follows:

$$U_i(p_d, p_c) = \Psi(p_d) - \Phi(p_d) - \sum_{v \in \mathcal{V}} C_v p_c, \quad (5)$$

where  $p_c$  is the unit price of cache storage.

To derive the profits of all network players involved in in-network caching, we formulate a market mechanism that satisfies both ISP and ICSPs via reverse auction model. The detail of the model is described in the rest of this section.

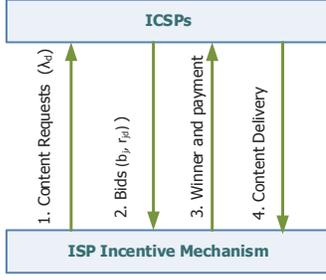


Figure 2: ISP Incentive Mechanism

## 2.1. ISP Incentive Mechanism Description

The ISP Incentive Mechanism workflow, depicted in the Fig. 2, is described as follows:

- First, for retrieving content requested by consumer  $u \in \mathcal{T}$ , the ISP floods content requests as demands  $\lambda_d$  to all transit links (step 1).
- Any bidder, which is an ICSP  $j \in \mathcal{N}$ , which has content  $d \in \mathcal{D}$  in its cache, returns bid  $(b_j, r_{jd})$  for content accessible on payment.  $b_j$  represents the content price submitted by bidder  $j \in \mathcal{N}$ , and  $r_{jd}$  represents the size of content  $d \in \mathcal{D}$  of each bidder  $j \in \mathcal{N}$  (step 2).
- The ISP evaluates the bids through the use of reverse auction, and generates results, where the bidder  $j \in \mathcal{N}$  with the lowest bid wins the auction. After the winner and payment determination, the ISP informs the winner for content delivery (step 3).
- For the delivered content, the ISP caches it, and forwards it to the consumers based on their demands (step 4).

## 2.2. Auction Model

In the ISP Incentive Mechanism, we use Reverse Auction (RA) [11]. RA helps the ISP to get prices from multiple ICSPs, and then the ISP selects price that minimizes its total payment.

For designing our auction model, we assume that each bidder  $j \in \mathcal{N}$  submits its valuation for content  $d \in \mathcal{D}$  without knowing the bids of other bidders. The ISP collects all the bids and checks whether the content size  $r_{jd}$  specified in each bid  $b_j$  meets the content size  $r_{id}$  needed by the ISP, i.e.,  $r_{jd} \geq r_{id}$ . However, in CCN, it is challenging to know the size of the content before receiving it. Thus, ISP requests content through flooding requests/ Interest Packets. In additional, CCN caching is based on packet level.

To deal with the above challenges, and being inspired by Apriori Algorithm [12] in Data Mining, we propose frequency-based content checking for finding frequent content size over all the content sizes submitted by bidders to prevent each bidder  $j \in \mathcal{N}$  from bidding and delivering small size of content than the needed content size. To control the content size and price, we assume that all packets of the same content/file have the common prefix in content name [13]. Therefore, for a given content size  $r_d = (r_{1d}, \dots, y_{Nd})$  submitted by bidders in RA, at each step, the ISP counts the occurrence of each content

size. The content size with maximum counts/support will be considered as baseline content size  $r_{id}$  required by ISP.

**Definition 1 (RA).** In Reverse Auction (RA), each bidder  $j \in \mathcal{N}$  submits one bid for each content  $d \in \mathcal{D}$  requested by ISP. The cost of bidder  $j$  for the content  $d \in \mathcal{D}$  is denoted by  $V_j$ , where  $v_j$  is the true valuation of the content  $d \in \mathcal{D}$ .

$$V_j(r_{id}) = \begin{cases} v_j, & j \in \mathcal{N}, \\ +\infty, & \text{otherwise.} \end{cases} \quad (6)$$

The content  $d \in \mathcal{D}$  for which the bidder  $j$  does not submit bid is assigned with an infinity cost.

**Definition 2 (Bidder Utility).** The utility  $U_j$  of any bidder  $j \in \mathcal{N}$  is defined as the difference between the price  $p_d$  received from the ISP and its true valuation  $v_j$  of the content  $d \in \mathcal{D}$ .

$$U_j = \begin{cases} p_d - v_j, & \text{if bidder } j \in \mathcal{W}, \\ 0, & \text{otherwise,} \end{cases} \quad (7)$$

where  $\mathcal{W}$  is the set of the winners. However, each bidder  $j \in \mathcal{N}$  will choose to participate if and only if  $p_d^* \geq v_j$ , i.e., its utility is not negative.

**Definition 3 (Individual Rationality).** RA is individually rational if and only if no bidder  $j \in \mathcal{N}$  receives negative utility, i.e.,  $U_j$  is not negative ( $U_j \geq 0$ ).

**Definition 4 (Truthfulness).** RA is truthful if and only if, for each bidder  $j \in \mathcal{N}$ , bidding the truth value  $(v_j, r_{jd})$  is the dominant strategy. In other words, bidding  $(v_j, r_{jd})$  maximizes the utility of each bidder  $j \in \mathcal{N}$  given for all possible values of other bidders.

Since bidders are strategic and selfish, we consider that it may be possible for any bidder  $j \in \mathcal{N}$  to submit its bid  $(b_j, r_{jd})$  which deviates from the true value  $(v_j, r_{jd})$ . By Definitions 2 and 3, we aim to ensure truthful bidding, where  $b_j = v_j$ .

In our RA, we use Vickrey–Clarke–Groves (VCG) mechanism [14]. The VCG mechanism efficiency can be achieved, in RA, through choosing the bid that minimizes total valuation rather than maximizes it by solving the following equation:

$$\operatorname{argmin}_{r_{jd}} \sum_{j \in \mathcal{N}} b_j(r_{jd}). \quad (8)$$

Let us consider  $v_N$  as the total valuation for all bidders that satisfy the content size  $(r_{id} = r_{jd}^*)$  needed by ISP, where  $v_N$  is equal to:

$$v_N = \sum_{j \in \mathcal{N}} b_j(r_{jd}^*). \quad (9)$$

Let  $v_{-j}$  denote the total valuation without bidder  $j \in \mathcal{N}$ , which is equal to:

$$v_{-j} = \sum_{k \in \mathcal{N} \setminus \{j\}} b_k(r_{kd}). \quad (10)$$

From (9) and (10), the price that the ISP needs to pay to bidder  $j \in \mathcal{N}$  is equal to:

$$p_d^* = v_{-j} - \sum_{k \neq j} b_k(r_{kd}^*), \quad (11)$$

and the utility function of each bidder  $j \in \mathcal{N}$  defined in (7) now becomes:

$$U_j = p_d^* - v_j. \quad (12)$$

The equations (12) and (11) have to grant the truthful bidding described in Definition (4) when  $b_j = v_j$ , where  $v_j$  represents the true valuation of the bidder  $j \in \mathcal{N}$ .

**Theorem 1.** *The RA is truthful.*

*Proof.* We assume that each bidder  $j \in \mathcal{N}$  wins the auction by bidding its true valuation, where  $b_j = v_j$ . We show that RA satisfies monotonicity and critical payment conditions for truthful bidding defined in [15].

- *Monotonicity:* Let us consider that each bidder  $j \in \mathcal{N}$  bid  $b'_j$  and  $b_j$  for content  $d \in \mathcal{D}$ , such that  $b'_j < b_j$ . RA selects the winner, which has the bid that minimizes total valuation in an increasing order of the bids. Therefore,  $b'_j$  will also make bidder  $j \in \mathcal{N}$  a winner of the auction, thus  $b'_j$  is less than  $b_j$ .
- *Critical payment:* RA pays every winner based on its bid and the bids of others, and tries to make social optimal allocation. The RA still makes bidder  $j \in \mathcal{N}$  with minimum bid as the winner whatever other bidders bid, and winner  $j \in \mathcal{N}$  gets paid  $p_d^* \geq b_j$ .

**Theorem 2.** *The RA is individually rational.*

*Proof.* As defined in [15], and by Definition 3, RA becomes individually rational if no bidder receives negative utility, while loser receives zero utility. Based on the above Theorem 1, RA makes bidder  $j \in \mathcal{N}$  with minimum bid as the winner whatever other bidders bid and gets paid  $p_d^* \geq b_j$ , which is equivalent to  $U_j \geq 0$ .

### 2.3. Problem Formulation

We aim to design RA that minimizes the total ISP payment for getting the content. The RA Total Payment Minimization (RA-TPM) problem is expressed as follows:

$$\min_{x_{jd}} \sum_{j \in \mathcal{N}} x_{jd} b_j(r_{jd}) \quad (13)$$

$$\text{s.t.} \quad \sum_{j \in \mathcal{N}} \sum_{d \in \mathcal{D}} x_{jd} r_{jd} \leq C_l, \quad \forall j \in \mathcal{N}, d \in \mathcal{D}, l \in \mathcal{L} \quad (14)$$

$$\sum_{j \in \mathcal{N}} \sum_{d \in \mathcal{D}} x_{jd} \leq 1, \quad \forall j \in \mathcal{N}, d \in \mathcal{D} \quad (15)$$

$$\sum_{j \in \mathcal{N}} \sum_{d \in \mathcal{D}} x_{jd} r_{jd} \geq \sum_{d \in \mathcal{D}} r_{id}, \quad \forall j \in \mathcal{N}, d \in \mathcal{D} \quad (16)$$

$$\sum_{j \in \mathcal{N}} \sum_{d \in \mathcal{D}} x_{jd} r_{jd} \leq \sum_{v \in \mathcal{V}} C_v, \quad \forall v \in \mathcal{V}, j \in \mathcal{N}, d \in \mathcal{D} \quad (17)$$

$$x_{jd} \in \{0, 1\}, b_j \in [0, +\infty), \quad \forall j \in \mathcal{N}, d \in \mathcal{D}. \quad (18)$$

*Constraints:* In (14), the sum of all traffic must be less than or equal to the transit link capacity  $C_l$ . In (15), each content will be supplied by one winner  $j \in \mathcal{N}$ . The constraint in (16) refers to the free disposal, where the total content size for each bidder  $j \in \mathcal{N}$  must be greater than or equal to content size  $r_{id}$  needed by the ISP. For the constraint in (17), the total content delivered on payment, and needs to be cached must be less than or equal to cache capacity of the ISP.

*Variables:* We use a set  $\mathcal{X}$  of binary decision variables  $\{x_{1d}, \dots, x_{Nd}\}$ , where  $x_{jd} = 1$  if bidder  $j \in \mathcal{W}$ , and  $x_{jd} = 0$  otherwise.

*Proposed Algorithms:* In order to reduce the computational complexity of our Integer Linear Programming (ILP) problem defined in (13), which is NP-hard, we solve the problem in two stages through the use of two algorithms, namely Winner Determination (WD) in stage 1 and Price Determination (PD) in stage 2.

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#### Algorithm 1 Winner Determination (WD) Algorithm

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1: Input:  $\mathcal{N}, b, r_d$ ;
2: Output:  $\mathcal{W}, \mathcal{X}, v_N$ 
   //Initialization;
3:  $\mathcal{W} \leftarrow \emptyset, \mathcal{X} \leftarrow (0, \dots, 0), v_N \leftarrow 0,$ 
    $F \leftarrow r_d, R \leftarrow (0, \dots, 0)$ ;
4: while  $F \neq \emptyset$  do
5:    $count[r_{id}] \leftarrow 0$  // Support count initialization;
6:   for all  $r_{id} \in F$  do
7:      $count[r_{id}] = count[r_{id}] + 1$ ;
8:   end for
9:    $R \leftarrow \{r_{id}, (count[r_{id}])\}$ ;
10: end while
11: Find content  $r_{id}$  with maximum count  $count[r_{id}]$  in  $R$ ;
   // Baseline content size
12:  $r_{id} \leftarrow r_{id}$ ;
13: for all  $b_j \geq 0, j \in \mathcal{N}$ , and  $r_{jd} \geq r_{id}$  do
14:   //Find distributor  $j \in \mathcal{N}$  which has minimum bid
    $j = \min(b)$ ;
15:    $v_N \leftarrow v_N + b_j(r_{jd})$ ;
16:    $\mathcal{W} \leftarrow \mathcal{W} \cup \{j\}$ ;
17:    $\mathcal{N}' \leftarrow \mathcal{N} \setminus \{j\}$ ;
18:    $x_{jd} \leftarrow 1$ ;
19:    $\mathcal{X} \leftarrow x_{jd}$ ;
20: end for
21: Return:  $\mathcal{W}, \mathcal{X}, v_N$ ;

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The inputs of Algorithm 1 include a set of bidders, vector of bids  $b$ , and content size  $r_d$ . At the line 3, the algorithm initializes the set of winners  $\mathcal{W}$ , the vector of content size  $F$ , total valuation  $v_N$ , and the vector of content size  $R$ . It counts the occurrence of each content size (lines 4 – 9), and then returns at line 12 the content with maximum support count as a baseline for the content size needed by ISP.

Algorithm 1 executes the winner determination for the positive bids, and content size submitted in each bid  $b_j$  greater than or equal to the content size  $r_{id}$  needed by the ISP (line 13). At line 14, Algorithm 1 finds the bidder  $j \in \mathcal{N}$  that has minimum bidding price, computes the total valuation (line 15), and includes bidder  $j$  into the winner set  $\mathcal{W}$  (line 16). At line 17, the algorithm excludes bidder  $j$  in  $\mathcal{N}$ . At the end, the

Table 1: Evaluation Settings 1

$T$	$N$	$b_j$	$r_{jd}$	$V$	$C_v$
[1, 000, 10, 000]	50	[2, 8]	[5, 500]	200	100
[10, 000]	50	[2, 8]	[5, 500]	50	[100, 1, 000]

algorithm returns a singleton set  $\mathcal{W}$  of winners, the set of decision variables  $\mathcal{X}$ , and total valuation  $v_N$  of all bidders.

### Algorithm 2 Price Determination (PD) Algorithm

- 1: **Input:**  $\mathcal{N}, \mathcal{N}', \mathcal{X}, \mathcal{W}, v_N, b, r_d, r_{id}, C_l, c_v$ ;
- 2: **Output:**  $p_d^*$ ;  
// Initialization
- 3:  $\mathcal{W}' \leftarrow \emptyset, p_d^* \leftarrow 0, v_{-j} \leftarrow (0, \dots, 0)$ ;
- 4: **for all**  $b_k \geq 0, k \in \mathcal{N}'$ , and  $r_{kd} \geq r_{id}$  **do**
- 5: //Find distributor  $k \in \mathcal{N}'$  which has minimum bid  
 $k = \min(b)$ ;
- 6:  $\mathcal{W}' \leftarrow \mathcal{W}' \cup \{k\}$ ;
- 7:  $v_{-j} \leftarrow v_{-j} + b_k$
- 8: **end for**
- 9:  $p_d^* \leftarrow v_{-j} - v_N$
- 10: //Feasible solution checking  
 $\sum_{j \in \mathcal{N}} \sum_{d \in \mathcal{D}} x_{jd} r_{jd} \leq C_l$ ;  
 $\sum_{j \in \mathcal{N}} \sum_{d \in \mathcal{D}} x_{jd} r_{jd} \leq \sum_{v \in \mathcal{V}} c_v$ ;
- 11: **Return:**  $p_d^*$

The Price Determination Algorithm 2 takes the set  $\mathcal{W}$  of winner as an input at line 1, in addition to the set of ICSPs ( $\mathcal{N}$  and  $\mathcal{N}'$ ), set of decision variables  $\mathcal{X}$ , vector of bids  $b$ , total valuation  $v_N$ , content sizes ( $r_d, r_{id}$ ), cache capacity  $c_v$ , and link capacity  $C_l$ , then computes the optimum price  $p_d^*$ .

First, at line 3, Algorithm 2 initializes the optimal payment  $p_d^*$ , the set of winners  $\mathcal{W}'$  for each bidder  $k \in \mathcal{N}'$ , the vector of total valuation  $v_{-j}$  without bidder  $j \in \mathcal{W}$ . For each bidder  $k \in \mathcal{W}'$ ,  $\mathcal{W}' \subset \mathcal{N}' \setminus \{j\}$ , the algorithm calculates the total valuation without  $j \in \mathcal{W}$  (lines 5–7). At line 9, the algorithm calculates the optimum price  $p_d^*$ , and checks the feasibility solution based on the constraints of RA-TPM problem defined in (13) at line 10. At the end, it returns the optimum  $p_d^*$  (line 11).

**Theorem 3.** *The computational complexity of RA is  $O(n^2)$*

*Proof.* In Algorithm 1, the first loop (lines 4–10) takes  $n^2$  iterations for counting the occurrence of each content size and each count is attached to the content size, in which  $n$  is considered as the size of the vector  $r_d$  of content size. The second loop (lines 13–18) takes  $n$  iterations to find the bidder  $j \in \mathcal{N}$  which has the minimum bid than the other bids. Therefore, for Algorithm 1, the computational complexity becomes  $O(n^2 + n)$ . Furthermore, Algorithm 2 uses  $n - 1$  iterations for finding minimum valuation without bidder  $j$  in the main loop. Hence, the computational complexity of Algorithm 2 becomes  $O(n - 1)$ , which is linear time. In conclusion, the computational complexity of RA is  $O(n^2)$ .

## 3. Performance Evaluation

In this section, we present in detail the performance evaluation of our proposal. During the evaluation, we use numerical analysis, where Julia language [16] is used.

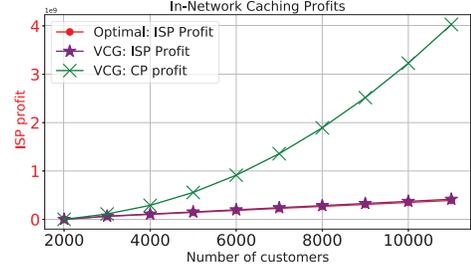


Figure 3: Monthly ISP profit

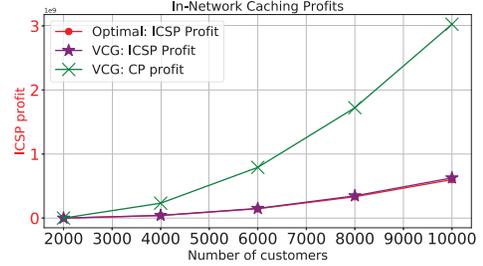


Figure 4: Monthly ICSP profit

## 3.1. Experimental Setup

In our experimental setup described in Table 1, we consider two settings. In the first setting, we fix the number of bidders to be  $N = 50$ , the number of routers to be  $V = 200$ , the cache capacity to be  $C_v = 100GB$ , and we vary the number of consumers from  $T = 1,000$  to  $T = 10,000$ . The number of requests are from 138601 to 246200 files. In the second setting, we fix the number of consumers to be  $T = 10,000$ , bidders to be  $N = 50$ , number of routers to be  $V = 50$ , and we change the cache size from  $C_v = 100GB$  to  $C_v = 1000GB$  in each router  $v \in \mathcal{V}$ . Furthermore, the bid  $b_j$  and content size  $r_{jd}$  of each bidder  $j \in \mathcal{N}$  are generated randomly from the ranges and distribution given in the table 1.

We derive the ISP profit based on (5), where monthly access bandwidth fee that each consumer  $u \in \mathcal{T}$  has to pay to its ISP is set to 50 USD [8] per 1 Gbps. Internet transit fee per unit of data  $\gamma_l$  is set at 0.63 USD per 1 Mbps [17]. Furthermore, the average cost of each 1 MB of memory is set at  $p_c = 0.003625$  USD.

We derive the ICSP profit, based on method for content distribution and reselling proposed by Kreuzer *et. al.* [18]. For each content  $d \in \mathcal{D}$  sold (from the second time sold content), the ISP as a content retailer receives 15% of  $P_d^*$  to compensate its caching cost, and transfer 85% to ICSP  $j \in \mathcal{W}$ . On the other side, each ICSP  $j \in \mathcal{W}$  receives 15% of  $P_d^*$  as a content distributor, and transfers remaining 70% to the CP.

## 3.2. Simulation Results

In Figs. 3, 4, 5, the first baseline method for our reverse auction is VCG mechanism. The VCG mechanism can be used to solve WDP once overall [19], once each bid is analyzed in turn and outputs with a winner through the use of WD Algorithm 1, and the price of the content through the use

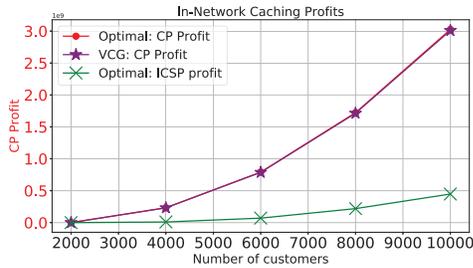


Figure 5: Monthly CP monthly profit

of PD Algorithm 2. Furthermore, we compare the solution of RA-TPM problem defined in (13) from VCG with the solution computed through the use of Gurobi optimization solver [20], the simulation results show that our algorithms perform closely to the optimal approaches.

The Fig. 3 shows the monthly profits of the ISP from in-network caching, where the number of customers is varied between 1,000 and 10,000 per day. Customers pay both Internet access fees and content fees. The ISP caches the content based on demands, i.e, ISP caching is not based on prefetching caching. This results in increasing the ISP’s profit linearly.

In Fig. 4, ICSP caching is based on prefetching caching, where contents are cached first, and wait to be requested later. From the beginning, the profit of ICSP  $j \in \mathcal{W}$  does not increase due to cost of caching which is compensated with transit fees. Once the number of consumers is more than 2000, the ICSP’s profit starts to increase.

Fig. 5 shows the profit of CP. The increase of the CP’s profit is based on the payment received from ICSP  $j \in \mathcal{W}$  for each content sold. The ISP pays to ICSP  $j \in \mathcal{W}$ , while ICSP  $j \in \mathcal{W}$  pays to CP based on content distribution, and the resell is used in this paper as a baseline.

## 4. Conclusion

In-network caching helps the ISP to increase profit through reducing network traffic crossing its network, and customers receive the content with reduced delay. However, CPs do not have control over ISP caching of its contents. For paid contents, if the ISP caches such contents inside its network, where the CP does not have access, it complicates the CP’s task of controlling content distribution. To address this challenge, an incentive mechanism between ISP and ICSPs that considers the content caching and distribution in the ISP network was discussed in detail in this paper. The simulation results show clearly that the mechanism increases their profits. For the future work, we plan to improve our incentive mechanism with more analysis and comparison.

## Acknowledgment

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.02-2015.36.

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