Optimizing Content Delivery in ICN Networks by the Supply Chain Model

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***Abstract*—Information-Centric Networking (ICN) is proposed to address the inefficiency of content delivery of IP networks from the perspective of architecture. In contrast, Content Delivery Network (CDN) is an overlay solution in current IP networks. We believe that even though ICN is fully deployed, there is still a role for CDNs to play in ICN networks. Since ISPs in ICN will replicate and forward contents according to their policies and interests, it may not align with the objectives of Content Providers (CPs). Therefore, CPs are willing pay a third party (i.e., CDN providers) a certain fee to meet their own requirements.**

In this paper, we propose to use the inventory model of Supply Chain Management (SCM) in logistics to formulate the content delivery process of ICN networks. The product-centric model of SCM is well-suited for the content-centric content delivery process of ICN networks. Also, we propose the system framework of inventory Centric Delivery Network (iCDN). Simulation results show that the average cost and link usage of the SCM-based algorithm can be reduced by 52% and 15% respectively compared to the baseline approach.

I. Introduction

Content delivery is becoming one of the most important activities in the Internet. According to the forecast of Cisco [1], by 2019, 80-90% of the global Internet consumption will be video content, and non-PC devices (e.g., smartphones and tablets) will account for 67% of the total traffic. Content Delivery Network (CDN) was invented in the late 1990s to tackle the scalability of content delivery issue of IP networks. Nowadays, it is the most widely used approach of content delivery in the Internet. Akamai, a well known CDN provider, deploys more than 200,000 surrogate servers in more than 1,400 networks all over the world, and carries 15-30% of all Web traffic in the Internet [2]. Akamai improves user experience of its customers (e.g., Microsoft, Yahoo!) by placing their contents in its surrogate servers, thus making them closer to end users.

In addition to the CDN approach, researchers of the network community are devoted to the issue of inefficient content delivery from the perspective of network architecture. Information-Centric Networking (ICN) has attracted many interests in the research community in recent years. ICN consists of a series of proposals which care about "what" rather than "where" [3]–[5]. It is proposed to tackle many intrinsic problems introduced by the IP architecture, such as inefficiency of content delivery, mobility, multicast, and security.

It is widely accepted that ICN can improve content delivery efficiency by in-network caching and nearest replica routing mechanisms. So, whether it still needs the content accelerating service of CDN in ICN networks is a moot point at present. The literature normally regards ICN as an implementation of CDN/P2P in the network layer [6], [7]. In this paper, we believe that the business model of CDN will still exist in ICN networks, and the ubiquitous caching will not eliminate the demands of customized content delivery. First, Content Providers (CPs) are normally enthusiastic to buy the access accelerating service for their contents, since user-perceived performance can greatly affect their revenue. Second, in order to maintain the neutrality of the Internet, Internet Service Providers (ISPs) only provide a non-discriminatory and best-effort packet delivery service. So it cannot satisfy the customized needs of CPs.

Designing a content delivery system in ICN networks is very different from the situation of IP networks. First, the network layer of ICN can natively support nearest replica routing, in-network caching and load balance. Therefore, these important functionalities, which are usually implemented by CDNs at the application layer are no longer needed in ICN networks. Second, one of the most important goals of CDNs is overcoming the flash crowd issue for CPs. However, the pervasive caching and multicast of ICN networks will dramatically mitigate this issue. Third, ISPs in ICN networks can replicate contents and announce them to other domains by routing protocols. So, in order to accelerate the access of their contents, CDN providers in ICN networks only need to pay ISPs certain fees to let their contents reside in the domain.

Supply Chain is a concept in the field of logistics, and it depicts a series of activities of large companies, such as manufacturing, inventory, transportation, etc. The model of Supply Chain Management (SCM) is widely adopted by large manufacturers all over the world. Evidences show that SCM can greatly improve productivity and save costs [8].

The SCM model is well-suited for content delivery in ICN. First, product delivery has a similar process compared with content delivery. Products are usually distributed to several

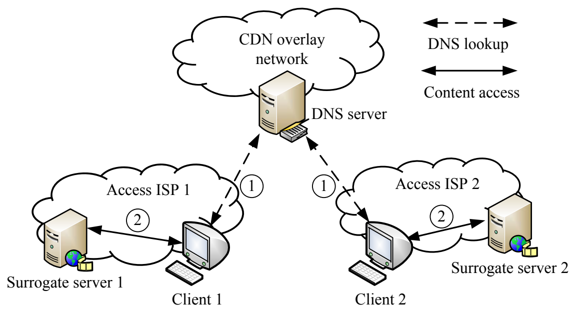


Fig. 1: The process of content delivery in CDN.

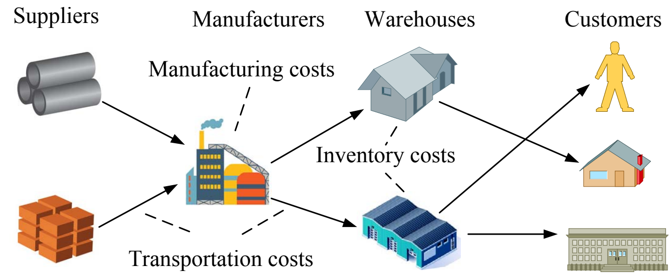


Fig. 2: An overview of the logistics network.

warehouses, then users can obtain them from a location nearby. Similarly, in ICN networks, contents are widely replicated, and requests can be forwarded to the nearest replica accordingly. Second, the SCM model is product-centric, and it cares about products rather than other factors. Similarly, ICN advocates a content-centric thinking in its architecture. Third, a chain supermarket (e.g., Wal-Mart) manages the inventory of its warehouses to satisfy fluctuated needs of its customers, much the way a CDN provider adjusts content placement according to the fluctuation of user requests.

In this paper, we make the following contributions.

- We propose the system framework of inventory Centric Delivery Network (iCDN) to tackle the content delivery issue of ICN networks.
- We use the inventory model of SCM to formulate the content delivery process of ICN networks.
- We use real Internet topology datasets to drive the simulation, and results show that the average cost and link usage of content delivery can be reduced by 52% and 15% respectively compared to the baseline approach.

The rest of the paper is organized as follows. Section II presents the background of CDN and SCM, then we propose our design of iCDN in Section III. Then, we present the elastic inventory model in Section IV. We present a baseline algorithm and a SCM-based algorithm in Section V. Then we present our simulations in Section VI. Section VII addresses the related work. Section VIII concludes our work.

II. Background

In this section, we start with reviewing the content delivery mechanism of ICN networks and propose that the demands of paid content delivery service will still exist. Then, we revisit the content delivery model of CDN in IP networks. Last, we introduce the overview of SCM in logistics.

A. Demands of CDN in ICN networks

The main usage of the Internet is accessing contents. ICN is proposed to tackle the inefficiency of content delivery of the current IP architecture. The content-centric thinking of ICN endows the network layer more content-aware capabilities, such as in-network caching or nearest replica routing [9], [10].

Most works in ICN focus on improving user experience or optimizing network resources from users' or ISPs' perspective rather than CPs'. In fact, CPs care more about the user experience of their own contents. Since user experience of CPs' contents will directly affect their revenue, they are normally willing to pay a CDN provider a high price to accelerate the access of their contents. As a result, the user-oriented and ISP-oriented approaches cannot fully satisfy the demands of CP-oriented services, and CPs still need the service of CDN providers. Even though some contents are neither popular nor would be popular from an ISP's perspective, CPs are willing to pay ISPs a certain fee to let them reside in ISPs' networks to improve performance.

B. Current CDN Model in IP networks

CDN was invented in the late 1990s to tackle the scalability of content delivery issue of IP networks. If a website distributes its contents by a single server or even a cluster of servers, its service quality cannot be guaranteed as user requests grow. When a flash crowd occurs, the huge amount of traffic ensued can overload the origin server or cause congestion on links nearby. CDN solves this issue by replicating the contents in surrogate servers all over the world, and redirecting user requests to the nearest (or least load) surrogate server (as shown in Fig. 1).

A CDN system normally consists of the following components [6], [11]. (1) *Surrogate server platform*. The surrogate servers are organized as an overlay network, and contents of customers are transported or updated to surrogate servers via this overlay network. This component also determines which contents to replicate and how long they will stay in the surrogate servers; (2) *Mapping system*. This is the key component of the system. It normally uses DNS or HTTP redirection techniques to map user requests to the most appropriate servers; (3) *Communications and control system*. This component monitors the status of the network and the load of surrogate servers by proactive or reactive measurements and reports the results to the mapping system; (4) *Data collection and analysis system*. This component records logs and generates all kinds of statistics.

C. SCM Inventory Model

A logistics network consists of suppliers, manufacturers, warehouses, and customers. After the process of manufacturing, products are distributed to warehouses owned by retailers, then they will be delivered to customers worldwide (as shown in Fig. 2). Supply Chain Management (SCM) is proposed to mange the processes involved in the logistics network, "So that merchandise is produced and distributed at the right

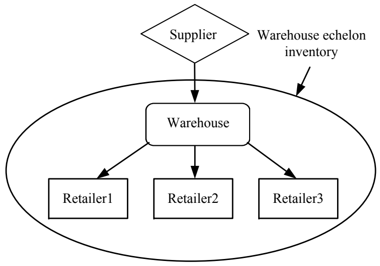


Fig. 3: The warehouse echelon inventory.

quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service level requirements [8]."

Inventory management is an important issue in SCM. It has two major objectives: (1) dealing with the variability of customer demands and (2) ensuring the service quality of product delivery. Since it is very difficult to precisely predict customer demands, the supply process can be smoothed if some products are reserved in stock in advance. Also, customers can obtain the products with less lead time, so the service quality is improved.

Fig. 3 illustrates the overview of *echelon inventory*, which involves several facilities (e.g., warehouses or retailers) owned by the same firm [8]. Products of the supplier are initially distributed to the warehouse, then redistributed to retailers where customers can buy them. Since the firm has the global information, it can minimize the overall costs by optimizing the echelon inventory of all the facilities.

Inventory and transportation strategies are two key components in the SCM literature. According to [12], the costs of General Motors is reduced by 26% annually by optimizing shipment size (inventory strategy) and routes (transportation strategy). IBM's spare parts distribution system can yield a 10% improvement in parts availability at the lower echelons, thus saving costs of \$20 million per year [13]. Similar to the inventory strategy and transportation strategy, it is widely agreed that caching and routing strategies are two key components in ICN networks.

To the best of our knowledge, we have not seen similar research work of using the concept of inventory management in logistics to model the content delivery process in the ICN literature. In this paper, we explore the feasibility of applying the product-centric inventory model in SCM to optimize content delivery in ICN networks.

III. Design Model

In this section, we start with the comparison of similarities and differences of content delivery and product delivery. Then, we explore the privileges of ICN, and propose that the inventory model of SCM is well-suited for content delivery in ICN networks. Then, we present the system framework of inventory Centric Delivery Network (iCDN).

A. Content Delivery vs. Product Delivery

1) Similarities: First, they both involve similar entities. In content delivery, they are CPs, CDN providers, ISPs, and users. In product delivery, they are manufacturers, wholesalers, retailers, and customers. Second, the delivery process is similar. Contents/Products are firstly distributed to several locations (i.e., surrogate servers/warehouses), then users can obtain them from a location nearby. Third, customer demands of contents/products are variable and hard to predict, so some contents/products are needed to keep in stock to make the delivery process smooth. Forth, the service quality perceived by users/customers can greatly affect the revenue of CDNs/retailers.

2) Differences: Although there are many similarities between content delivery and product delivery, we cannot simply apply the models of SCM to content delivery in ICN networks. They have the following differences. First, the consumption of contents and products is different. Content delivery only duplicates and transmits digital data to users, while product delivery transfers the physical products from retailers to customers. Second, the payment model is different. In content delivery, CPs pay CDN providers for the content delivery service.[1] Whereas in product delivery, customers pay retailers for the price of products. Third, the consequence of being out of stock is different. The miss of contents in a surrogate server will induce redirection of the requests to other servers, and it might not cause severe performance degradation. In contrast, when products are out of stock, it will induce long lead time to order them.

B. The Privileges of ICN

The main objective of ICN networks is delivering contents rather than connecting nodes of IP networks. The following privileges of ICN make the inventory model of SCM more suitable to the situation.

1) Content-Centric and Pervasive Caching: In ICN networks, content becomes the first citizen. Contents can be requested, cached, replicated, forwarded, signed and verified as independent elements in ICN networks [3], [5], [14]. The content-centric feature makes the flow of contents in ICN very similar to the flow of products in SCM. Products can be manufactured, transported, stocked, and consumed by retailers and customers. In some sense, SCM can be regarded as a product-centric network.

2) Nearest Replica Routing and Adaptive Forwarding: Requests can be routed to the nearest replica when multiple copies of the same content exist in the network [14]. In addition, unlike the simple forwarding of IP routers, ICN routers can forward requests according to the current network status (e.g., link failure or congestion) even before routing state converges [15]. In a word, nearest replica routing and adaptive forwarding are natively supported by the network layer of ICN.

C. System Framework

Our design of iCDN is based on the following assumptions. First, the network layer of ICN networks takes full responsibility of forwarding requests to the nearest (or least load) replica.

[1] Although CPs do not gain profit from users directly, they can earn profit from advertising if they can attract a large volume of user traffic.

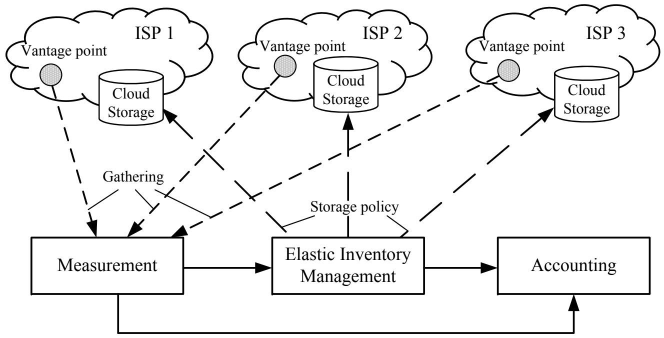


Fig. 4: An overview of iCDN in ICN.

Second, we envision that cloud service will be available in most ISP networks. So an iCDN provider has finer granularity to decide how much storage they need to allocate in every Autonomous System (AS). Nowadays, some CDN providers (e.g., Limelight) already deploy their surrogate servers in a few large Data Centers. Whereas, Akamai deploys their surrogate servers in ISPs' networks, and trades the flexibility of managing resources for better performance [16]. In ICN networks, we assume that an iCDN provider has both the advantages of Limelight and Akamai. They can dynamically determine the capacity of storage and content placement in each AS, and adjust them according to the status of requests and the network.

The overview of iCDN is shown in Fig. 4. The system consists of three components: (1) *Measurement component* uses proactive or reactive methods to collect status data (such as request popularity, replicated contents, and service quality) by widespread vantage points, then reports them to other components; (2) *Elastic inventory management component* calculates the optimal policy for each decision making cycle after receiving the status data from measurement component. The policy decides a) which locations (i.e., ASes) to apply storage and how much is needed, and b) which contents to place at each location; (3) *Accounting component* generates bills according to the statistic data from other components, such as the access rate of surrogate servers and the service quality it provides.

Compared to the traditional CDN systems, iCDN has the following advantages. First, it can apply and release storage from ISPs according to the status of requests and the network. In contrast, CDNs nowadays either have limited coverage (e.g., Limelight) or have no power to adjust storage dynamically (e.g., Akamai).[2] Second, iCDN does not need to rely on a complicate mapping system to redirect user requests to nearest replicas. In fact, ISPs have more accurate information (e.g., topology, congestion, or link failure) to make wiser routing and forwarding decisions, so we can leverage these features supported by the network layer of ICN networks. Third, iCDN can utilize all the contents cached in the network. For example, if some videos are popular and already widely cached in the network by ISPs, iCDN providers can evict them from their storage to save costs.

IV. Elastic Inventory Model

We use the term of *elastic inventory* to describe the manipulation of storage by iCDN providers. It is more elastic compared with the inventory management of products in SCM, since we assume that storage can be applied and released at any time or location without extra overhead. As a result, an iCDN provider only needs to make a tradeoff between operation costs (e.g., storage and bandwidth costs) and the service quality it can provide. If contents are widely replicated in the network, the service quality is improved. The operation costs, however, will increase accordingly. Otherwise, less replicated contents may cause service quality degradation.

The functionality of our elastic inventory model is similar to the Order Assignment System (OAS) in SCM. OAS takes charge of assigning orders to depots based on inventory status and the associated transportation costs. It has a vehicle routing system to determine the optimal routes of delivering customer orders [13]. Similarly, our elastic inventory management component also takes charge of determining inventory level of each AS. In contrast, the routing process is provided by the ICN network layer.

We formulate the elastic inventory problem in iCDN as follows. The objective of our model is minimizing the costs of iCDN providers, and it includes the costs of storage and bandwidth.[3] The decision variable is the inventory level of each AS in this decision cycle. The constraints include the service quality of users (measured in delays), the bandwidth capacity, and the availability of contents in the network.

$$\begin{aligned}
&Minimize && \sum_{i=1}^{N}\sum_{k=1}^{M} x_i^k S_k P_i + \sum_{i=1}^{N}\sum_{k=1}^{M} \lambda_i^k S_k Q_i \\
&Subject\ to: && Delay_i^k = Min\{D_{ij} | A_j^k = 1 \vee x_j^k = 1\} \\
& && Delay_i^k \leq DelayLim \\
& && \sum_{k=1}^{M} \lambda_i S_i x_i^k \leq BW_i \\
& && x_i^k \in \{0,\ 1\} \\
& && A_i^k \in \{0,\ 1\} \\
& && i, j = 1, \ldots, N \\
& && k = 1, \ldots, M
\end{aligned} \tag{1}$$

The notations are defined as follows. Let x_i^k denote the decision variable, which is a binary variable and indicates whether storing content k in AS_i. Let λ_i^k denote the rate of user requests for content k from AS_i. Let A_i^k denote whether content k is already replicated in AS_i by ISPs or users. Let D_{ij} denote the measured delay from AS_i to AS_j. From the values of D_{ij}, x_i^k, and A_i^k, we can obtain the delay from AS_i

[2]There is a similar issue in SCM, and it is called Risk Pooling. For example, a company named ACME decides to reduce its two warehouses of different locations to one to save inventory costs, while the corresponding increasing of transportation cost ensued is acceptable [8].

[3]Note that we do not consider maximizing profit in this paper, since the revenue is determined by the volume of contents served, the quality of service and the contract agreement between iCDN providers and CPs, which we assume as constant. Therefore, the profit of an iCDN provider is mainly determined by its costs.

to content k, and let $Delay_i^k$ denote it. Let S_k denote the size of content k. Let P_i denote the price of storage of AS_i. Let Q_i denote the price of bandwidth of AS_i. Let $DelayLim$ denote the required service level measured in latency. Let BW_i denote the bandwidth capacity of AS_i.

Theorem 1. *The elastic inventory problem (shown in Equation 1) is NP-hard.*

Proof. We prove the theorem by reducing the *0-1 Multi-dimensional Knapsack Problem* (MKP) problem, which is known to be NP-hard [17], to the elastic inventory problem in polynomial time.

For each instance of the MKP problem, we construct an instance of the elastic inventory problem by making the assignments of $\forall i \forall j \ DelayLim = Max(D_{ij})$ and $\forall i \ Q_i = 0$. The constructed equations are as follows.

$$\begin{aligned} Minimize \quad & \sum_{i=1}^{N}\sum_{k=1}^{M} x_i^k S_k P_i \\ Subject\ to: \quad & \sum_{k=1}^{M} \lambda_i S_i x_i^k \le BW_i \\ & x_i^k \in \{0,\ 1\} \\ & i = 1, \ldots, N \\ & k = 1, \ldots, M \end{aligned}$$

The constructed instance of the elastic inventory problem is equivalent to the original instance of the MKP problem, and the construction can be done in polynomial time. This ends our proof. □

V. Algorithms

In this section, we present two algorithms to tackle the elastic inventory problem. The main difference between the baseline algorithm and the SCM-based algorithm is the content-based routing process. The baseline algorithm adopts the *shortest path toward the origin* approach, while the SCM-based algorithm adopts the *nearest replica routing* approach. The former approach represents web caching in IP networks, whereas the latter approach can fully take advantage of the content-aware routing feature of ICN networks.

A. Baseline Algorithm

We devise a baseline algorithm shown as Algorithm 1. The algorithm can be divided into two phases. Phase 1 finds all ASes that can satisfy the required service quality (i.e., delay limit) for each AS_i and each content k, and the produced set of ASes can be denoted as ASN_i^k. If the requested content k has already been replicated within those ASes (i.e., $j \in ASN_i^k \wedge A_j^k = 1$), the requests can be satisfied instantly; Phase 2 greedily stores those bandwidth hungry contents to cheaper ASes. The computational complexity of the algorithm is $O(M \cdot N^2 \cdot logN)$, and it is mainly determined by the sorting process of Phase 2.

Algorithm 1: Baseline algorithm

```
Input: λ_i^k, S_k, P_i, D_i^j, A_i^k, Path_i^k, SL, BW_i, N, M
Output: Inventory strategy x_i^k
∀i  x_i ← 0
∀i ∀k  ASN_i^k ← φ
/* Phase 1: Find all ASes within DelayLim for each AS_i and
   content k, then set λ_i^k zero if the requests can be satisfied */
for i ← 1 to N do
    for k ← 1 to M do
        for j ← 1 to N do
            if D_i^j ≤ DelayLim and j ∈ Path_i^k then
                ASN_i^k ← ASN_i^k ∪ {j}
        foreach j ∈ ASN_i^k do
            if A_j^k = 1 then
                λ_i^k = 0
/* Phase 2: Greedily store contents which consume more
   bandwidth, and choose cheaper ASes greedily */
Sort({λ_i^k S_k | i = 1,...,N  k = 1,...,M})
for r1 ← 1 to MN do
    λ_i^k ← r1^th largest value of {λ_i^k S_i}
    Sort({P_j | j ∈ ASN_i^k})
    for r2 ← 1 to |ASN_i^k| do
        j ← r2^th smallest value of ASN_i^k
        if BW_i − λ_i^k S_k ≥ 0 then
            x_i^k ← 1
            BW_i ← BW_i − λ_i^k S_k
            Break
return x_i^k
```

B. SCM-Based Algorithm

We devise a SCM-based algorithm shown as Algorithm 2. The algorithm can be divided into three phases. Phase 1 finds all ASes that can satisfy the required service quality (i.e., delay limit); Phase 2 excludes those requests that can be satisfied by the replicated contents of ASes; Phase 3 greedily stores those bandwidth hungry contents to cheaper ASes (similar to Phase 2 in Algorithm 1). The computational complexity of the algorithm is $O(M \cdot N^2 \cdot logN)$, and it is mainly determined by the sorting process of Phase 3.

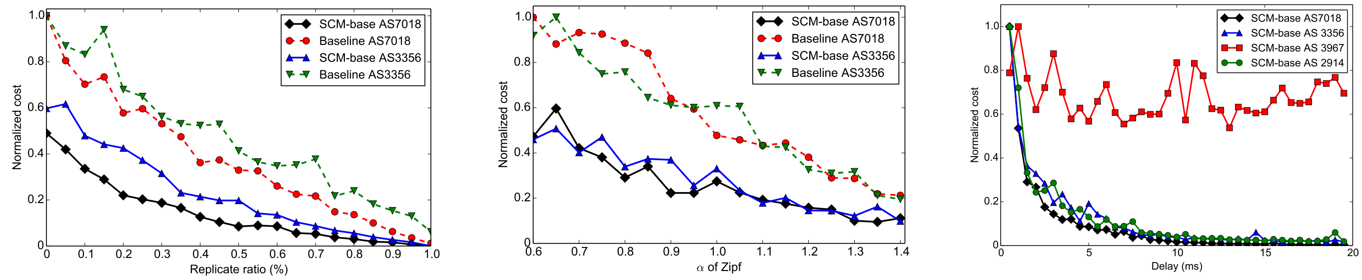
VI. Evaluation

In this section, we present the methodology of our request-level simulation and the simulation results.

A. Methodology

Real topology dataset: We use real ISP topology dataset of Rocketfuel [18] to drive the simulation. The overview of the 9 ASes of the simulation is shown in Table I.[4] The dataset has the PoP-level topology of every AS, such as the core routers, the links and their delays, the PoP locations, and neighbouring ASes. We treat each PoP as the root of a three layer complete binary tree, and requests all stem from the leaves.[5]

[4] We only found 9 out of the 10 ASes mentioned in [19] in the dataset.
[5] It is similar to the simulation topology used in [20].



(a) Cost of increasing replication ratio (delay limit = 3ms, and Zipf $\alpha = 0.7$).

(b) Cost of increasing Zipf α (delay limit = 3ms, and replication ratio=20%).

(c) Cost of increasing delay limit (Zipf α = 0.7, and replication ratio=20%).

Fig. 5: Comparison of cost with increasing of replication ratio, Zipf α, and delay limit.

Algorithm 2: SCM-based algorithm

Input: $\lambda_i^k, S_k, P_i, D_i^j, A_i^k, SL, BW_i, N, M$
Output: Inventory strategy x_i^k

$\forall i \quad x_i \leftarrow 0$
$\forall i \quad ASN_i \leftarrow \phi$
/* ***Phase 1***: Find all ASes within $DelayLim$ */
for $i \leftarrow 1$ ***to*** N **do**
  for $j \leftarrow 1$ ***to*** N **do**
    if $D_i^j \leq DelayLim$ **then**
      $ASN_i \leftarrow ASN_i \cup \{j\}$
/* ***Phase 2***: Exclude satisfied requests */
for $i \leftarrow 1$ ***to*** N **do**
  for $k \leftarrow 1$ ***to*** M **do**
    foreach $j \in ASN_i$ **do**
      if $A_j^k = 1$ **then**
        $\lambda_i^k = 0$
/* ***Phase 3***: Greedily store contents which consume more bandwidth, and choose cheaper ASes greedily */
Sort($\{\lambda_i^k S_k \mid i = 1, \ldots, N \quad k = 1, \ldots, M\}$)
for $r1 \leftarrow 1$ ***to*** MN **do**
  $\lambda_i^k \leftarrow r1^{th}$ largest value of $\{\lambda_i^k S_i\}$
  Sort($\{P_j \mid j \in ASN_i\}$)
  for $r2 \leftarrow 1$ ***to*** $|ASN_i|$ **do**
    $j \leftarrow r2^{th}$ smallest value of ASN_i
    if $BW_i - \lambda_i^k S_k \geq 0$ **then**
      $x_i^k \leftarrow 1$
      $BW_i \leftarrow BW_i - \lambda_i^k S_k$
      Break
return x_i^k

TABLE I: Information of ASes in Rocketfuel.

ASN	ISP Name	# Routers[6]	# Links	# PoPs
AS 1221	Telstra (Australia)	44	44	5
AS 1239	Sprintlink (US)	52	84	35
AS 2914	Verio (US)	70	111	28
AS 3257	Tiscali (Europe)	41	87	10
AS 3356	Level3 (US)	63	285	20
AS 3967	Exodus (US)	6	6	4
AS 4755	VSNL (India)	9	11	5
AS 6461	Abovenet (US)	19	34	14
AS 7018	AT&T (US)	115	148	33

Synthesized dataset: We generate the following synthesized dataset according to various distributions. (1) The request rates conform with Zipf's law, and we set the parameter α to 0.7 in most cases, which is verified in web contents [21]. (2) The number of requests is set to 10,000 during the simulation period. (3) The number of content types is 1,000, and the sizes of contents conform with Pareto distribution. We set the Pareto parameter α to 1.3, which is observed varying between 1 and 1.5 in web contents [22]. (4) The average size of web contents equals to 2.2 MB according to the latest report in [23]. (5) The bandwidth capacity of all the links between core routers is set to 40 Gbps. (6) The price of storage is randomly generated and the mean value is $0.05/GB$ according to the data of [24]. (7) The price of traffic is twice of the price of storage.

Experimental setup: We implement the simulation program in Python and upload the source code online.[7] All the experiments are carried out on a workstation, which runs a Ubuntu 14.04 operating system and has a 2-core Intel i3-2350M 2.3 GHz CPU and 6 GB of memory. Each experiment is carried out 10 times and we calculate the average value for each metric.

B. Results on Costs

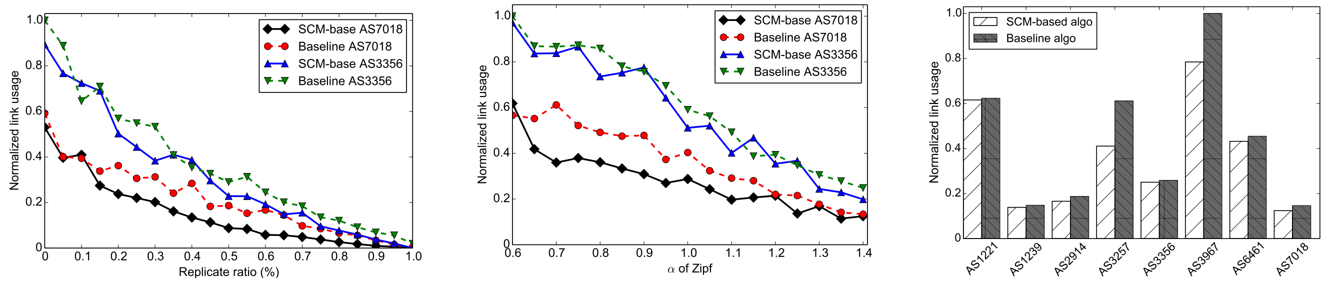
Fig. 5 shows the normalized costs of several selected ASes in different scenarios. The reasons that we select AS 7018 and AS 3356 in Fig. 5(a) and Fig. 5(b) mainly rely on the fact that these two ASes have more routers and links, so it results in less fluctuations. There is no baseline algorithm in Fig. 5(c), since only the SCM-base algorithm has the salient feature of tuning the service quality of delay to make a balance between cost and performance.

Fig. 5(a) shows that when increasing the replicate ratio, costs can be reduced accordingly. It is understandable because more contents can be obtained from AS caches, so the costs of iCDN can be saved. The SCM-based algorithm always outperforms the baseline algorithm. The costs of AS 7018 and AS 3356 can be reduced by 62% and 52% respectively.

Fig. 5(b) shows that when increasing the value of α of Zipf, costs can be reduced accordingly. When the value of α is large, the popular contents becomes more concentrated. Therefore,

[6]Note that routers here denote core routers.

[7]The source code is available at https://github.com/fengz10/ICN_SCM.



(a) Link usage of increasing replication ratio (delay limit = 3ms, and Zipf $\alpha = 0.7$).

(b) Link usage of increasing Zipf α (delay limit = 3ms, and replication ratio=20%).

(c) Comparison of link usage of various ASes (delay limit = 3ms, Zipf $\alpha = 0.7$, and replication ratio=20%).

Fig. 6: Comparison of link usage with increasing of replication ratio and Zipf α.

many requests focus on few pieces of content, and they can be satisfied by AS caches easily, so the costs of iCDNs will decrease accordingly. The SCM-based algorithm always outperforms the baseline algorithm. The costs of AS 7018 and AS 3356 can be reduced by 55% and 50% respectively.

Fig. 5(c) shows that when increasing the value of delay limit, costs can be reduced accordingly. Accordingly, the service quality is degraded at the same time. AS 3967 in Fig. 5(c) has more fluctuations and no improvement of cost when increasing the delay, since it is a small ISP and it has less core routers and limited coverage, and nearly all the core routers are within the scope of 3ms. Therefore, cost cannot be saved by relaxing the delay limit. The SCM-based algorithm endows iCDN operators the privilege to tune the service quality requirement (by tuning the delay limit) to make a tradeoff between cost and performance.

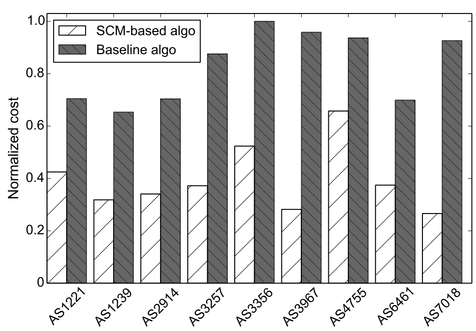


Fig. 7: Comparison of cost of various ASes (delay limit = 3ms, Zipf $\alpha = 0.7$, and replication ratio=20%).

Fig. 7 shows the costs of all 9 ASes in a typical setting (i.e., delay limit = 3ms, Zipf $\alpha = 0.7$, and replication ratio=20%). The SCM-based algorithm always outperforms the baseline algorithm, and the average cost can be reduced by 52%.

C. Results on Link Usage

Fig. 6 shows the normalized link usage of AS 7018 and AS 3356. The reason that we select those two ASes is the same as Section VI-B.

Fig. 6(a) shows that when increasing the replicate ratio, link usage can be reduced accordingly. It is understandable because more contents can be obtained from AS caches, so less bandwidth is consumed. The SCM-based algorithm always outperforms the baseline algorithm. The link usage of AS 7018 and AS 3356 can be reduced by 30% and 13% respectively.

Fig. 6(b) shows that when increasing the value of α of Zipf, link usage can be reduced accordingly. When the value of α is large, the popular contents becomes more concentrated. Therefore, many requests focus on few pieces of content, and they can be satisfied by AS caches easily, so the costs of iCDNs will decrease accordingly. The SCM-based algorithm always outperforms the baseline algorithm. The link usage of AS 7018 and AS 3356 can be reduced by 24% and 6% respectively.

Fig. 6(c) shows the link usages of all ASes in a typical setting (i.e., delay limit = 3ms, Zipf $\alpha = 0.7$, and replication ratio=20%). The SCM-based algorithm always outperforms the baseline algorithm. The average link usage can be reduced by 15%.

D. Summary of Simulation Results

The key observations from the simulation results are:

- The average cost and link usage of content delivery can be reduced by 52% and 15% respectively compared to the baseline approach.
- The SCM-based algorithm endows iCDN operators the privilege to tune the service quality requirement (by tuning the delay limit) to make a tradeoff between cost and performance.
- Fayazbakhsh et al. states that the performance gap between shortest path and nearest replica is negligible (at most 2%) [20]. Their work focuses on the scenario of static provisioning of storage and bandwidth. In contrast, we assume the storage and bandwidth can be applied dynamically, so the improvement is much more appealing.

VII. Related Work

Content delivery in ICN. ICN is a hot research issue in recent years, and many schemes have been proposed in the field [3]–[5]. Most research work in the field focuses on the issues of caching strategy or content based routing [9], [10]. Jiang et al. propose a content delivery mechanism called nCDN to leverage the advantages of ICN [25]. Sevilla et al. suggest that the efficiency of ICN can be achieved in traditional IP networks by modifying the DNS records to map contents to IP addresses [26].

Unlike applying the ideas of ICN to the current IP networks [25], [26], in this paper, we focus on how to design a brand-new content delivery model for ICN networks. Our insight mainly comes from two intuitive questions. First, whether the CDN service is still necessary in ICN networks (the literature normally regards ICN as an implementation of CDN/P2P in the network layer [6], [7])? Second, if so, what is the key issue of designing a CDN service in ICN networks? For the first question, our answer is yes (see Section II-A), and for the second one, we believe the inventory management will become the main issue since nearest replica routing will be provided by the network layer of ICN networks natively (see Section IV).

Content delivery in CDN. Large content providers usually use CDN service to accelerate their content delivery. CDN can improve user experience, scalability, and security by deploying wide spread surrogate servers in access networks of ISPs [6]. Nygren et al. present the design and implement of Akamai, which is the most well-known CDN provider [11]. Yu et al. study the tradeoffs of designing throughput oriented CDNs, which dominate the traffic in the Internet nowadays [16]. It concludes that the number of peering points plays a more important role compared with path selection and multipath routing of ISPs. All the work above focuses on CDN in IP networks, however, we focus on designing a CDN system in ICN networks.

Supply Chain Management. SCM is a well-developed research field in logistics, and it attracted many research interests more than a decade ago [8], [13], [27]. Many big firms (such as Wal-Mart) develop their own SCM to improve efficiency and reduce cost [8]. Many mathematical models have been proposed in SCM, such as warehouse location selection model, transportation optimization model, inventory management model, and consumer demands prediction model [13], [27], [28].

In our prior work, we employ the SCM charging model to redefine the business relationship between ISPs to facilitate the deployment of ICN networks [29]. In this paper, however, we employ the SCM inventory model to formulate the content delivery process of ICN networks. To the best of our knowledge, there has no similar research work in the network literature using SCM models.

VIII. Conclusion

We propose the framework of inventory Centric Delivery Network (iCDN) to address the content delivery issue in ICN networks. Then, we introduce an inventory strategy model of SCM to formulate the optimization problem. Simulation results show that the SCM-based algorithm can reduce the average cost and link usage of content delivery by 52% and 15% respectively compared to the baseline approach.

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