Content Routing and Lookup Schemes using Global Bloom Filter for Content-Delivery-as-a-Service

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***Abstract*—Leveraging cloud computing technology, we have proposed content-delivery-as-a-service (CoDaaS) to distribute user generated content (UGC) in an efficient and economical fashion. However, due to the exponential increases of Internet traffic, traditional hashing-based content routing and lookup scheme suffers from high delay. This paper introduces a global compressed counting bloom filter (CCBF) into CoDaaS to address this issue. The global CCBF adds our system with the capability to early check the existence of any specific content among all the peering surrogates, before any local checking on each cache node. Using this global CCBF, we propose two content routing and lookup mechanisms (parallel and cut-through schemes) to reduce the delay for better user experience. We verify the comparative performance of those approaches via both mathematical modeling and experimental simulation. The results show that for light traffic load, the mean response time can be saved by up to 65.2%. Besides, the impacts and overheads of different synchronization schemes for the CCBF are quantified to provide valuable insights for further optimizations.**

I. Introduction

The rapid growth of user-generated content (UGC) on the Internet stresses existing content distribution networks (CDNs), and its unique characteristics require novel schemes for the processing and distribution. UGC is currently one of the fastest growing forms of contents [1]. In 2008, 42.8% of Internet users in the U.S contributed to the UGC, and this ratio is expected to reach 51.8% by 2013. UGC, due to its long-tail nature and unique features (e.g., conversational media, social interaction, etc), posits additional challenges for its delivery. On the other hand, the leading CDNs service providers (e.g., Akamai, Limelight, etc), tailor their network architecture and operational structure towards popular contents. As a result, it is difficult to distribute heavily long-tailed contents over CDNs in a profitable way. We have previously proposed a novel architecture, Content-Delivery-as-a-Service (CoDaaS) [2], [3], by leveraging cloud computing technologies, to distribute UGCs in the most economic manner.

In addition to the cost objective, the proposed CoDaaS also aims to provide the best possible user experience to the content consumers. One of the quality-of-service (QoS) objectives is to minimize the request response time [4]. The response time basically depends on two processes in content distribution, including content route and content lookup. In traditional CDNs [5]–[7], these two processes are normally executed in sequential order, which directly translates into poor QoS in terms of high lookup latency and consequent long response time. In CoDaaS, we seek to reduce the request response time by parallelling these two processes.

In this research, we introduce a global bloom filter into CoDaaS to minimize the request response time. Specifically, the global bloom filter is maintained by all the surrogates in CoDaaS, to represent the existence of cached contents. It provides the capability to make an early decision on whether the requested content is cached in the CoDaaS before the request is routed to the designated server. Compared to traditional CDNs, our approach executes content route and lookup processes in parallel. As a result, the request response time can be reduced, providing an improved user experience.

Our contributions are multi-fold, including:

- We propose two content routing and lookup schemes (i.e., parallel and cut-through), using the global bloom filter to reduce the response time.
- We introduce a mathematical model to justify the potential gain of our proposed content routing and look schemes, and analyze their limitations.
- We quantify the performance gain and the overhead of our proposes schemes via a system-level simulation. Our numerical results suggest that, for light-loaded traffic (e.g., Twitter-like applications), the average request response time for our proposed content routing and lookup schemes can be reduced by up to 65.2%, compared to the sequential one. Our simulation results also suggest mechanisms to optimize the proposed schemes to reduce the impact of false positive inherent to BF, and false negative and the traffic overhead, resulting from the BF synchronization.

These results provide a fundamental basis to understand the benefits of using bloom filter for content routing and look up, and offer operational guidelines to optimize the design of CoDaaS for best possible user experience.

The rest of the paper is organized as follows. In Section II, we show some related works. In Section III, we present the system architecture for CoDaaS and the proposed schemes by using bloom filter for content routing and lookup. In Section IV, we introduce a mathematical model to examine the potential gain and the overhead of the content routing and lookup schemes. In Section V, we outline the simulation environment and present the numerical results. In Section VI, we summarize the paper and point out potential future works.

II. Related Work

Pervious researches on content routing design for CDNs mainly focused on the hashing-based approaches. The hashing-based method [5] was proposed to route the content request to desirable surrogate according to the hash value. Another semi-hashing-based scheme [6] was proposed to strike a balance between local hit ratio and cluster hit ratio. Other schemes were also proposed to improve the CDNs performance, including load and proximity-aware routing scheme [7], and decentralized replica-selection for cloud services [8].

Bloom filter (BF) [9] was also used intensively for network applications. Cache digest [10] uses BF to indicate the existence of local cached replications. L. Fan et al. introduced counting bloom filter (CBF) for web cache sharing to improve the Internet Cache Protocol (ICP) [11]. BF also was used to route content within Internet routers [12].

Our work differentiates from these pervious researches in several aspects. First, we use BF to jointly optimize the two processes of content routing and lookup for content delivery. Second, our design objective is to minimize the request response time, which can be translated into a better QoS. Finally, we introduce a mathematical framework to justify the validity of our proposed scheme and the performance gain is verifies by a system-level simulation over CDNsim [13].

III. System Overview

In this section, we present a schematic overview of the Content-Delivery-as-a-Service (CoDaaS) architecture, and then explain the concept of bloom filter. Finally, we propose two alterative schemes, based on the usage of a global bloom filter, to improve the content routing and lookup scheme.

A. CoDaaS Architecture

The CoDaaS architecture consists of a media cloud, content providers and consumers. The media cloud is made of a list of interconnected virtual machines (VMs), which are instantiated in geographically distributed data centers. The set of VMs can form a CDN overlay dynamically to cache and render contents. Content providers can publish their contents in origin servers with a specified service level agreement (SLA). The content consumers experience a better QoS with the controlled content distribution. The resources consumed by the CDN overlay can be scaled up and down to meet application demand, thus reducing the total cost of ownership. More details about CoDaaS can be found in [2], [3].

In Figure 1, we illustrate the joint process of content routing and lookup for CoDaaS. When the consumer requests a content, the request, after entering the CoDaaS system, will be routed from its ingress point to the designated server. The designated server will do a content lookup in its local storage to determine whether the content has been cached. In case of a cache hit, the content will be served from the designated server to the users. In case of a cache miss, the content will be retrieved from the origin server and then served to the users. In CoDaaS, we aim to optimize these two processes to reduce the response time, by introducing a global bloom filter.

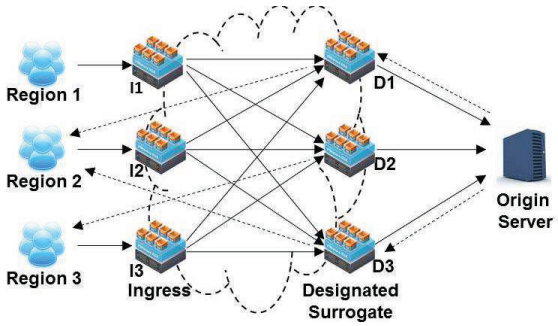


Fig. 1: Content routing and lookup scheme for CoDaaS

B. Global Bloom Filter

1) Bloom Filter and Its Variation: In this paper, we use a *compressed counting bloom filter*, which is a variation of standard BF, for content routing and lookup in CoDaaS.

A standard bloom filter (BF) is a bit array of m bits to represent a set of n elements S, by using k independent hash functions $h_1, h_2...h_k$. For each element s in S, it sets each $h_i(s), i = (1, 2...k)$ bit to 1 for insertion. To check the existence of any element x, it checks whether all the $h_i(s), i = (1, 2...k)$ bits are 1. Due to the hashing collision, a false positive [9] may occur with the probability as

$$f_{bf} \approx (1 - e^{-kn/m})^k. \quad (1)$$

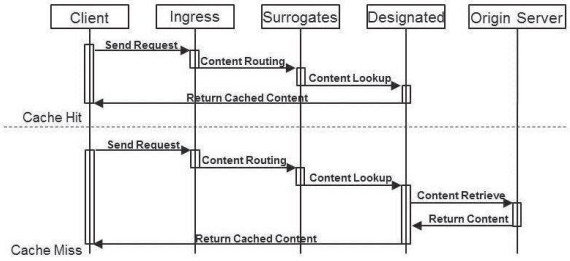
The counting bloom filter (CBF) is derived from the standard BF. It uses m fixed size integers instead of m single bits for presence. For an insertion or deletion operation, the corresponding counters increase or decrease by 1. Thus, CBF provides the deletion capability. In this work, we use four bits counters to construct our CBF, which has been shown to be sufficient for most network applications [11].

To reduce the transmission size of CBF as a message, compressed counting bloom filter (CCBF) is used. This work adopts the multi-layer compressed counting bloom filter (ML-CCBF) [14] that uses the run-length code to encode CBF messages. This encoding process can save up to 50% of the transmission traffic. Moreover, we also use a Delta compression scheme to further reduce the transmission size by only transferring the changes for each layer in our CCBF.

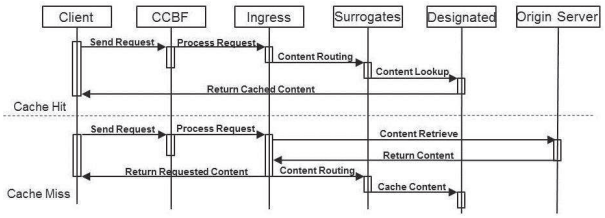
2) Synchronization Schemes: Synchronization is a process of establishing consistency of the global bloom filter among all the surrogates by exchanging sync messages. In this research, we consider two alternative trigger schemes for CCBF synchronization. One is the periodic update mode, in which each surrogate broadcasts its update in a regular interval. The other is the event-driven update model, in which the broadcast is triggered by some predetermined events (e.g., the reception of a fixed number of requests). These two sectionalization modes will have different impact on the performance gain and the overhead, as verified in Section V.

C. Workflows for Content Routing and Lookup Schemes

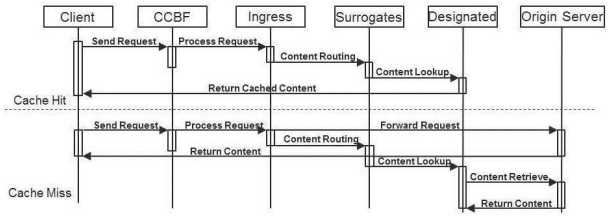
In this paper, as illustrated in figure 2, we consider three alternative content routing and lookup schemes for CoDaaS.



(a) Sequential Scheme



(b) Parallel Scheme



(c) Cut-through Scheme

Fig. 2: Workflow diagrams for three alternative content routing and lookup schemes in CoDaaS

Figure 2-(a) illustrates the workflow of the traditional scheme, in which content routing and lookup processes are executed sequentially. In a DHT-based scheme, the routing process takes on average $\lceil \log_2 N \rceil$ hops to reach the designated server, where N is the active number of the surrogates in CoDaaS. The content lookup process starts when the request is routed to the designated server. For the cache hit case, the designated server immediately replies to the user. Otherwise, it will retrieve the content from its origin server and then render it to the consumer.

The key idea in this research is to use a global CCBF to determine whether the request content has been cached in CoDaaS, at the ingress point of each request. This early decision offers a chance for CoDaaS to retrieve the content in parallel with the request routing. Using this insight, we propose two content routing and lookup schemes for CoDaaS, including a parallel scheme and a cut-through scheme.

Figure 2-(b) illustrates the workflow of the parallel scheme. In case of a cache miss, the ingress directly acquires the content from its origin server. The ingress server, upon receiving the content from the original server, renders the content to the consumer and forward a copy to the designated server for caching. This scheme executes content routing and content lookup in parallel, thus reducing the request response time.

Figure 2-(c) illustrates the workflow of the cut-through scheme. Upon a cache miss, the ingress redirects the request from the user directly to the origin server. At the same time, the request is routed to the designated server, which will retrieve a copy of the content directly from the original server for caching purpose. This scheme reduces the request response time significantly by cutting through the CoDaaS system; however, it increases the traffic load to the origin server.

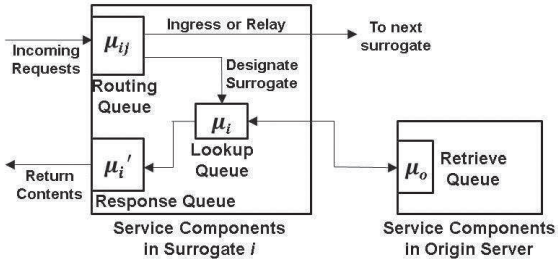


Fig. 3: Service Components for Content Routing and Lookup

In next two sections, we will compare the performance of these three schemes analytically and numerically.

IV. Mathematical Formulation

In this section, we develop a mathematical model to compare the performance of the aforementioned three schemes for content routing and lookup in CoDaaS.

A. Latency for Content Routing and Lookup

1) System Stability: We first ensure the system is stable to keep every service queues are finite.

The request arrival process at ingress I_i for a particular content c, can be modeled as a Poisson process with mean arrival rate λ_i^c. The ingress server I_i serves these requests with a rate of μ_{ij}, at which they will be forward to their designated surrogate D_j. We assume the capacity of the routing path is $C_{ij}, (i \neq j)$. Thus, the system stability condition is given by,

$$\sum_{\forall c} \lambda_i^c < \sum_{\forall j} \{min(\mu_{ij}, C_{ij})\}. \tag{2}$$

In CoDaaS, each surrogate may either be the ingress, relay or the designated server to serve the requests. When surrogate i works as an ingress or a relay, it checks the routing table to determine the next hop for current requested content c. When surrogate i works as the designated server, it checks its own storage with the service rate μ_i to determine whether there is a cache hit or miss, denoted as p_c (0 for cache miss and 1 for cache hit). We refer μ_o as the serving rate at origin server, and C_o as the bandwidth capacity at origin server. The stability condition for the original server is given by,

$$\sum_{\forall i} \sum_{\forall c} \lambda_i^c (1 - p_c) < min(\mu_o, C_o). \tag{3}$$

2) Service Components for Content Routing and Lookup: As indicated in figure 3, there are several service components involved in the content routing and lookup process. They serve as the foundations to calculate the expected request repones time under a chosen scheme.

The routing process directs the requests from the ingress to their designated server. It can be viewed as a M/M/1 queue with the mean arrival rate λ_i^c and the mean service rate μ_{ij} at surrogate i. Thus, we have the mean routing latency T_r as,

$$\mathbb{E}[T_r] = \lceil log_2 N \rceil (\sum_{\forall j} \mu_{ij} - \sum_{\forall c} \lambda_i^c)^{-1}. \quad (4)$$

The lookup process occurs in the designated servers for each requests. It can be modeled as a M/M/1 queue with the service rate μ_i at surrogate i. Assuming the hash functions are well designed, the contents must be evenly distributed among all the surrogates. Thus, the mean content lookup delay T_l is,

$$\mathbb{E}[T_l] = (\mu_i - \frac{1}{N} \sum_{\forall i} \sum_{\forall c} \lambda_i^c)^{-1}. \quad (5)$$

For the cache miss cases, the content retrieve process, which also constructs a M/M/1 queue, is required at the origin server. Assuming α is cache hit rate and $1-\alpha$ is cache miss rate, we have the expectation of the content retrieve time T_o as,

$$\mathbb{E}[T_o] = (\mu_o - (1-\alpha) \sum_{\forall i} \sum_{\forall c} \lambda_i^c)^{-1}. \quad (6)$$

Finally, there exists a M/M/1 queue when designated surrogates j return the request content to users via its network card with service rate μ'_j. The mean content return time T_c is,

$$\mathbb{E}[T_c] = (\mu'_j - \sum_{\forall i} \sum_{\forall c} \lambda_{ij}^c)^{-1}. \quad (7)$$

3) Workflow Analysis: Figure 4 illustrates the processing models for the three content routing and lookup schemes. Analytic results are presented based on these models.

Figure 4-(a) shows the workflow of sequential scheme. Each incoming request in this way has to follow the content routing and the lookup process no matter there is a cache hit or a cache miss. Moreover, for a cache miss, it will cost extra T_o time to retrieve the content from origin server. At last, for both conditions, the designated surrogates returns the content to users only after all the previous requests are served. Thus, we have mean response time R_t for traditional scheme as,

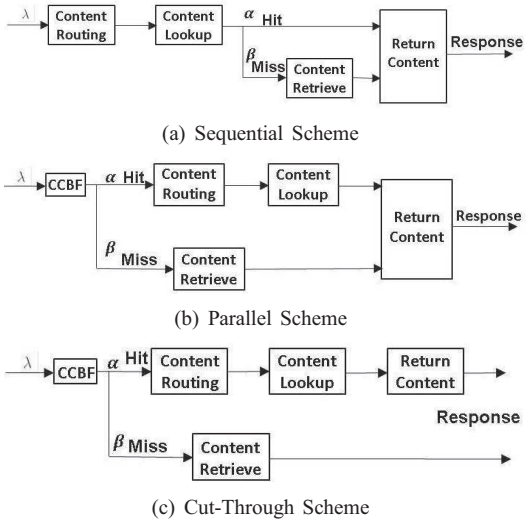
$$\mathbb{E}[R_t] = \alpha \mathbb{E}[T_r + T_l] + (1-\alpha)(\mathbb{E}[T_r + T_l] + \mathbb{E}[T_o]) + \mathbb{E}[T_c]. \quad (8)$$

The parallel scheme parallelizes the retrieve operation with the content routing and lookup process as shown in figure 4-(b). Hence, for a cache miss, T_r could be saved to make the response. However, the overhead of this operation includes both false positive f_p, false negative f_n and the extra sync messages. The mean response time R_p for this scheme is,

$$\begin{aligned} \mathbb{E}[R_p] &= (\alpha + f_p - f_n)(\mathbb{E}[T_r + T_l] + \tfrac{f_p \mathbb{E}[T_o]}{\alpha + f_p - f_n}) \\ &\quad + (1 - \alpha - f_p + f_n)\mathbb{E}[T_o] + \mathbb{E}[T_c]. \end{aligned} \quad (9)$$

The cut-through scheme further cuts the content return time from designated surrogate by redirecting requests to the origin server for cache misses as indicated in figure 4-(c). Thus the mean response time R_c for cut-through scheme is,

$$\begin{aligned} \mathbb{E}[R_c] &= (\alpha + f_p - f_n)(\mathbb{E}[T_r + T_l] + \tfrac{f_p \mathbb{E}[T_o]}{\alpha + f_p - f_n}) \\ &\quad + (1 - \alpha - f_p + f_n)\mathbb{E}[T_o]. \end{aligned} \quad (10)$$



(a) Sequential Scheme

(b) Parallel Scheme

(c) Cut-Through Scheme

Fig. 4: Processing Models on the Three Schemes

Nevertheless, the cut-through scheme doubles the traffic load at origin server for cache misses. Therefore, it may cause congestion, which can further lead to severe delay. Let η be the corresponding congestion factor [15], and S_c be the size of requested content. To avoid the congestion at the origin server, the following inequality must be satisfied,

$$2(1 - \alpha - f_p + f_n)\mathbb{E}[S_c] \sum_{\forall i} \sum_{\forall c} \lambda_i^c < \eta C_o. \quad (11)$$

B. Overhead of Importing Global CCBF

1) False Positive & False Negative: Two factors may lead to false positive, including the nature of CBF and the inconsistency problem when the cached content has been replaced. Since in CoDaaS, the cached content must be the most popular ones, and the requests follow zipf law [18], the false positive caused by inconsistency is negligible. As a result, the false positive f_p is roughly equal with f_{bf} as expressed by Eq. (1).

The false negative is only introduced by the consistency issues when each surrogate synchronize the global CCBF. Thus, it is affected only by the frequency of synchronization.

2) Synchronization Messages: Apart from the congestion that may occur at the origin server, the sync messages could also introduce jams inside the CoDaaS. For each surrogate i, its outcoming traffic consists of sync messages, content transfer and request forwarding. The overall traffic must not exceed its bandwidth capacity to avoid the traffic congestion.

For the parallel scheme, the content transfer occurs for both cache misses and hits. And for cache misses, this traffic will be doubled. Let λ_s as the sync rate, S_f as the size of CCBF, and S_r as the size of content request. The following inequality should be satisfied to avoid congestion,

$$\lambda_s \mathbb{E}[S_f] + ((2 - \alpha - f_p + f_n)\mathbb{E}[S_c] + \mathbb{E}[S_r]) \sum_{\forall c} \lambda_i^c < \eta \sum_{\forall j} C_{ij}. \quad (12)$$

Similarly, for cut-through scheme, the content transfer from surrogate to customers only happens for cache hits. Thus, the

congestion free condition for cut-through scheme is given by,

$$\lambda_s \mathbb{E}[S_f] + ((\alpha + f_p - f_n)\mathbb{E}[S_c] + \mathbb{E}[S_r]) \sum_{\forall c} \lambda_i^c < \eta \sum_{\forall j} C_{ij}. \quad (13)$$

V. Simulation and Results

This section provides the details on simulation methodology and settings. Then the analysis on the results are presented.

A. Simulation Methodology and Setup

1) Simulation Tool: We use CDNsim [13] to build our simulation environment. CDNsim is a discrete event simulation tool based on OMNeT++ library designed for CDNs. We modify some basic modules to fit our implementation and add the three content routing and lookup policies into this tool.

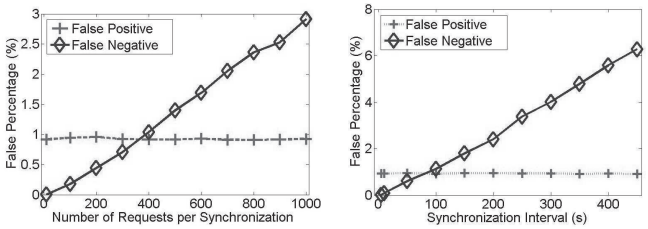
We simulate $N = 50$ homogenous VMs as geographically distributed surrogates to construct the media cloud inside the CoDaaS. All the surrogates are coordinated by a DHT ring using Chord protocol [16]. The modulo function is used to hash the identification of both contents and surrogates. The cache capacity of each surrogate is 2% of the total size of the objects in the origin server. And the cache replacement policy is Least Recently Used (LRU). We use GT-ITM [17] to generate a real Internet topology model, Transit-Stub model with 1008 routers dispersed at different areas. There is only one origin server, which hosts 50000 unique content objects with the total size of approximately 5GB retrieved from a social website. The service capacity is $500reqs/s$ for each surrogate, and $1000reqs/s$ for the origin server. We assume the size of each request occupies 60 Bytes (i.e., $S_{req} = 480bits$). Besides, we define the link capacity among all the nodes as $C_o = 100Mbps$, and $\sum_{\forall j} C_{ij} = 100Mbps$ for surrogate i.

We generate requests from 100 client groups with the mean interval time at 0.01 second (i.e., $\sum_{\forall i} \sum_{\forall c} \lambda_i^c = 100reqs/s$). The distribution of the interval time of all the request follows exponential distribution, and distribution of requested content follows zipf law [18] to make the access pattern much closer to realistic ones. In this setting, the stability of our CDN system can be ensured by satisfying both Eq. (2) and (3).

The hash functions of the bloom filter are built by dividing a 128-bits MD5 signature for each URL into four 32-bits words, and the modulus of each word by the number of counters are the hash values. The maximum volume of the counter bloom filter is set at 20Kb (i.e., 5000 counters) which is a reasonable size that can keep the false positive rate below 1% for zipf distributed enquires. We compress the global counting bloom filter using ML-CCBF [14]. And the delta compression algorithm is used to compress the sync message to further reduce the transmission size.

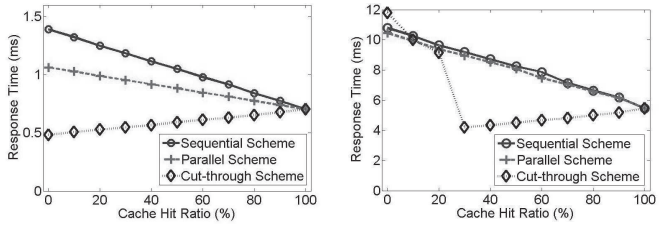
B. False Positive & False Negative

Figure 5 shows the relationship between synchronization frequency and false positives/negatives. We implement both periodical and event-driven sync schemes. The results indicate that the two schemes present almost the same trend. This can be attributed to the fact that for a given incoming pattern, the expectation for the inter-arrival time is fixed.



(a) Event-Driven Scheme (b) Periodical Scheme

Fig. 5: False Hit/Miss under Two Synchronization Schemes



(a) Light Traffic (b) Heavy Traffic

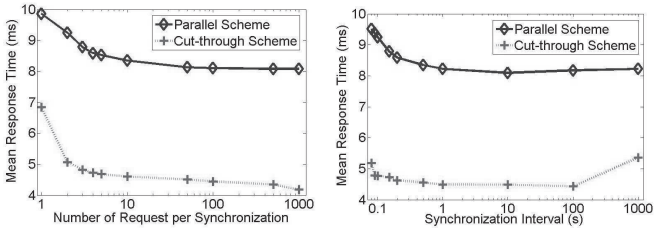
Fig. 6: User Perceived Response Time under Two Scenarios: (a) Popularity of Content is Inversely Proportional to Its Size; (b) Popularity of Content is Proportional to Its Size

As the interval increases, the false negatives increase accordingly, while the false positives maintain at a certain level as discussed in section IV-B. When the sync frequency is extremely high (i.e., one sync for every single request), there is no false negatives at all. But this setting could generate intensive synchronization traffic. When the frequency is higher than once per 400 requests for event-driven scheme or once per 100 seconds for periodical scheme, the false negatives can be controlled below 1 %. And in this case the traffic load could also be kept at a relatively low level.

C. Improvement on User Perceived Response Time

We simulate two scenarios to test our system. One is that the popularity of an object is inversely proportional to its size, that is, the smallest content is most popular. The other one is that the largest content has the highest popularity. Hence, the average size of requested content S_c for these two scenarios is around 32Kb and 170Kb respectively, to simulate different level of traffic load on data plane. The sync frequency for the global bloom filter is set at once per 400 requests using the event-driven scheme. Various cache hit rates are set by initializing the global bloom filter and the cached content in each surrogate. This simulation lasts for 1000 seconds. The results are presented by figure 6.

In the first scenario, the average response time of cut-through scheme is the lowest, while the traditional scheme costs the highest delay among all the three mechanisms, as expressed in Eq. (8) (9) (10). When there is no cache hit, the gap between our proposed schemes and the traditional one is the largest for all the cases. The parallel scheme and the cut-through scheme are able to reduce the mean response time by



(a) Event-Driven Sync Scheme (b) Periodical Sync Scheme

Fig. 7: Synchronization Frequency vs. User Response Time

23.6% and 65.2% compared with that required by the sequential one. As the cache hit ratio goes up, the performances of the three schemes get closer, because the workflows are the same for cache hits. Finally, when all the requests are cache hit, the results from the three policies arrive at the same point.

The interesting observation in figure 6-(a) is the mean response time of both traditional sequential scheme and parallel scheme decreases, while the time required by cut-through scheme increase, as the cache hit ratio raises. It indicates that as long as there is no traffic congestion (i.e., Eq. (11) is satisfied), it is advantageous to redirect the missed requests to origin server in terms of minimizing the response time.

In the second scenario, the parallel scheme still needs less response time than that of the sequential scheme for all the cases, while the cut-through scheme suffers from the congestion when the true cache hit rate is lower than 30%. But the cut-through scheme performs most efficiently again when the cache hit rate passes the congestion threshold as derived from Eq. (11). It may motivate us to adopt an adaptive algorithm, which adopts the cut-through scheme when there is no congestion, and dynamically changes into the parallel scheme when the cache miss rate exceed the threshold.

D. Impact of Synchronization Traffic

Figure 7 presents the relationship between the sync frequency and the response time. To investigate the impact of sync traffic on the response time, we experiment on a set of sync frequency based on both event-driven and time-driven to generate different levels of sync traffic. This simulation is under the condition that the popularity of content is proportional to its size, and the cache hit rate is 50%.

Figure 7-(a) shows how the sync frequency of event-driven scheme affects the response time. Specifically, the response time is much longer when the frequency is higher than once per 5 requests for both schemes. The reason can be attributed to the traffic jam inside CoDaaS as discussed in Eq. (12) (13). As the frequency continues to increase, the sync traffic load becomes lighter, but on the other hand, the false negative increases. Such combined effects make the response time lowest at the point of approximately one sync per 400 requests.

Figure 7-(b) shows how the frequency of periodical scheme affects the response time. The response time is constrained by the congestion inside the CoDaaS when the frequency is high (i.e., higher than 10 syncs per second). In contrast, when the frequency is extremely low (i.e., lower than one sync per 1000 seconds), the incurred false negative causes more faking cache misses. This further introduces congestion at origin server, and thus increases the response time.

VI. Conclusion and Future Works

In this paper, we propose parallel and cut-through content routing and lookup schemes by using a global compressed counting bloom filter (CCBF). Mathematical models are presented to analyze both the user perceived response time and the overheads of importing this CCBF, including false positive/negative, traffic congestion, and synchronization cost. Simulations are conducted to prove the performance of those metrics. The simulation results match well with our analytic models, indicating our proposed schemes can save up to 65.2% mean response time for light traffic loads.

Our future work will aim to a congestion-aware adaptive algorithm to further improve the efficiency of our content routing and lookup scheme for all the traffic loads. We will also aim to fully make use of VMs in CoDaaS, where the service rate and storage capacity can be dynamically adjusted.

References

[1] Paul Verna, A Spotlight on UGC Participants, online resource, http://www.emarketer.com/Article.aspx?R=1006914 (2009)

[2] Y. Wen, G. Shi, et. al., *Designing an inter-cloud messaging protocol for content distribution as a service (CoDaaS) over future internet*, 6th Int'l Conference on Future Internet Technologies, pp. 91-93, 2011.

[3] Y. Jin, Y. Wen, et. al., *CoDaaS: An Experimental Cloud-Centric Content Delivery Platform for User-Generated Contents*, 2012 Int'l Conference on Computing, Networking and Communication, pp. 934-938, 2012.

[4] J. Chen, SHG. Chan, VOK. Li, *Multipath routing for video delivery over bandwidth-limited networks*, IEEE JSAC, vol. 22, pp. 1920-1932, 2004.

[5] D. Karger, A. Sherman, et al., *Web Caching with Consistent Hashing*, Computer Networks, vol. 31, no. 11-16, pp. 1203-1213, 1999.

[6] J. Ni, and D. Tsang, *Large Scale Cooperative Caching and Application-level Multicast in Multimedia Content Delivery Networks*, IEEE Communications, vol. 43, pp. 98-105, 2005.

[7] M. Pathan, C. Vecchiola and R. Buyya, *Load and Proximity Aware Request-Redirection for Dynamic Load Distribution in Peering CDNs*, On The Move To Meaningful Internet Systems: OTM, 2008.

[8] P. Wendell, J. Jiang, et al., *DONAR: Decentralized Server Selection for Cloud Services*, ACM SIGCOMM 2010, pp. 231-242, 2010.

[9] B. Bloom, *Space/time tradeoffs in hash coding with allowable errors*, Communications of the ACM, vol. 13, no. 7, pp. 422-426, 1970.

[10] A. Rousskov and D. Wessels, *Cache Digests*, Computer Networks and ISDN Systems, vol. 30, pp. 2155-2168, 1998.

[11] L. Fan, P. Cao, et al., *Summary Cache: A Scalable Wide Area Web Cache Sharing Protocol*, IEEE/ACM Trans. on Networking, vol. 8, no. 3, pp. 281-293, 2000.

[12] M. Lee, K. Cho, et al., *SCAN: Scalable Content Routing for Content-Aware Networking*, IEEE ICC 2011, pp. 1-5, 2011.

[13] K. Stamos, G. Pallis, et al., *CDNsim: A Simulation Tool for Content Distribution Networks*, ACM Transactions on Modeling and Computer Simulation, 2009.

[14] D. Ficara, S. Giordano, et al., *Multilayer Compressed Counting Bloom Filters*, IEEE INFOCOM 2008, pp. 311-315, 2008.

[15] R. Banner and A. Orda, *Multipath routing Algorithms for Congestion Minimization*, IEEE/ACM Trans. on Networking, vol. 15, no. 2, pp. 413-424, 2007.

[16] I. Stoica, R.Morris et al., *Chord: A Scalable Peer-to-Peer Lookup Protocol for Internet Applications*, IEEE/ACM Transactions on Networking, vol. 11, no. 1, pp. 17-32, 2003.

[17] E. Zegura, K. Calvert, and S. Bhattacharjee. How to model an INternetwork, IEEE INFOCOM 1996, pp. 594-602, 1996.

[18] L. Breslau, P. Cue, P. Cao, et al., *Web caching and Zipf-like distributions: Evidence and implications*, IEEE INFOCOM 1999, pp.126-134, 1999.