Efficient Hierarchical Content Distribution using P2P Technology

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***Abstract*—CDN (Content Delivery Network) and P2P (Peer-to-Peer) are two dominant technologies in large-scale content distribution. However, they have their own advantages and disadvantages. In this paper, an efficient hierarchical content distribution scheme is proposed, integrating the traditional CDN and centralized P2P. In our approach, content distribution is divided into two stages. In the CDN-level core network, the content is strategically placed from central server to a set of edge servers, and edge servers can exchange content between each other to enhance efficiency. In the P2P-level logical access network, the content is distributed from edge server to user nodes, and the user nodes can concurrently download from both the edge server and other peer user nodes. Analytical results are given to demonstrate the performance of HCDN (Hierarchical Content Distribution Network).**

I. Introduction

With the growth of the Internet over the last decade, large-scale content distribution has been an intensively studied research topic. Some related applications become more and more popular, such as large-document media delivery, software distribution, and video streaming. They need meet the requirement of high speed, low latency and high scalability. To improve the quality of service (QoS), two dominant technologies have been proposed -- CDN (Content Delivery Network) [1] and P2P (Peer-to-Peer) [2][3].

In the CDN architecture, a number of surrogate servers which store copies of origin server's content are deployed strategically across the wide-area Internet. The content is disseminated from origin server to the surrogate servers. CDN systems direct content requests to the optimal surrogate server close to users. Hence users can access effectively with lower latency. Furthermore, CDN can significantly release the overload on origin server, reduce network congestion, and increase content availability. However, there are some limitations included in CDN, for example:

- High cost of deployment and maintenance.
- Limited capacity of surrogate servers.
- In essence, it is still client/server architecture, so the performance may degrade quickly when there are a great number of requests for one surrogate server.

In the P2P architecture, peers behave as servers as well as clients, and collaborate to exchange content. The file one peer downloads is often made available for uploading to other peers. The peers participate voluntarily, and can join or leave system at any time. The more peers are involved; the better performance can be achieved commonly. P2P has many advantages on scalability, fault tolerance, robustness and deployment cost. However, there are also some problems in P2P architecture to provide high quality of service:

- Low performance when there are insufficient peers.
- Limited computational resources of peers, for example, low uploading bandwidth and low storage space.
- Instability of dynamic peers.

To sum up, both CDN and P2P have their own advantages and disadvantages. The main goal of this work is to combine advantages of CDN and P2P to make up their own weakness and realize cost-effective large-scale content distribution.

The remainder of this paper is organized as follows. The related works are discussed in section II. The novel hierarchical architecture, integrating CDN and P2P, is presented in section III, including network model, system architecture and content distribution operations. We analyze the performance in section IV, comparing the hybrid architecture with traditional CDN and P2P. Section V shows the numeric results. Finally, the conclusion is drawn in section VI.

II. Related Work

In recent years, CDNs have been extensively applied to improve user experience. A growing number of content providers benefit from content distribution services offered by many companies like Akamai. Previous research has deeply investigated the CDN architecture, including replica placement algorithm, content routing, load balancing, request redirection, etc. In [4], the use and effectiveness, integrating CDN into the existing web architecture, are intensively studied. In [5], replica placement strategies are proposed to improve the distribution efficiency, and the load balance in core network has been discussed. A novel segmentation-based technique is presented for large media files in [6], its key feature is that the data distributed on a surrogate server is not whole document but fine-grained segments. In [7], a Video-CDN is described to deliver high-quality TV content. In [8], CDI (Content Distribution

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Internetworking) is widely studied, and its main purpose is to allow cooperation among separate CDNs.

On the other hand, P2P has been a killer application in the span of a few years. There has been a considerable amount of research work on P2P systems [9]. P2P systems can be classified into centralized, decentralized or hybrid architecture. A centralized solution relies on one node designated as an index server to provide location service for peers [10]. Such systems with the index server are simple, and they operate quickly and efficiently for locating. In decentralized P2P systems, no index server exists, and the processing steps of the application are divided among the participating nodes [11]. These systems are effective to avoid single point of failures and bottlenecks. In [12], hybrid P2P systems are proposed. In these systems, some of the nodes called "super node" play a more important role than the rest of nodes. These nodes maintain the central indexes for the location information shared by local peers, respectively.

To the best of our knowledge, there are only a few research work concentrated on integration of CDN and P2P. [13] has proposed a PM-CDN (P2P-based architecture Multimedia CDN), and load balance algorithms have been considered. However, in this scheme, P2P architecture is only used in CDN core network to support that surrogate servers can directly exchange content. CDN-P2P hybrid architecture is adopted for streaming media in [14], but it mainly focus on peer contribution strategy for media streaming. In [15], P2P-based techniques are introduced to form CDI cooperating among separate CDNs.

In this paper, we propose a hierarchical content distribution network (HCDN), in which the two-level hierarchical architecture is presented to distribute large-scale content, integrating CDN and P2P. The CDN system is setup in core network to disseminate the content from origin server to a set of surrogate servers; The P2P systems are constructed in the access network to allow the user can receive content from both the surrogate server and other peers owing the identical file.

III. Hierarchical Content Distribution

A. *Hierarchical Model*

Traditional CDN architecture can be presented to a client/server model, as shown in Fig.1(a). The content is deployed from origin server to surrogate servers, and the user nodes access content from the surrogate servers. The latency can be significantly reduced.

As shown in Fig.1(b), the centralized P2P architecture is described to an indexing model. The content is exchanged between user nodes, and the index server is only responsible for maintaining the indices. The user nodes communicate with index server for obtaining and updating indices. So, the overload of server is obviously reduced, and the scalability and robustness are improved.

The architecture of HCDN can be further abstracted to a two-level hierarchical hybrid model, as shown in Fig.1(c). The process of content delivery includes two stages: CDN-based and P2P-based. In core network, CDN system is deployed and the content is strategically disseminated on surrogate servers. In access network, the centralized P2P system is introduced, and the user nodes can exchange content between each other. So, user nodes can concurrently get content from both surrogate servers and other user nodes. The most notable advantage is that HCDN makes use of both CDN's and P2P's complementary advantages. Comparing with the traditional CDN architecture, HCDN can reduce the overload of surrogate servers; therefore the cost can be significantly decreased by deploying fewer surrogate servers. Comparing with pure P2P architecture, HCDN can provide high quality of service, avoiding the low performance of P2P when there are scarce peers in system.

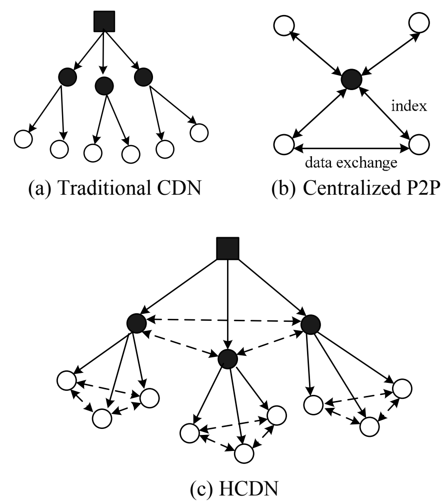

Fig. 1 Network Models of CDN, centralized P2P and HCDN

Note that, the reason we choose the centralized P2P is that it is of simplicity, controllability and efficiency for locating. It is also worth mentioning that the surrogate server and index server can be integrative or respective in system implementation.

B. *System Architecture*

The network topology of HCDN is shown in Fig.2. The system mainly includes three types of entities: central server, edge server and user nodes. The details are described as below.

Central Server is deployed in the core network, similar with the original server in traditional CDN, on which the distributed content can be initially placed. The central server maintains deployed content information of every edge server. It also plays an important role on placement strategies, determining where files should be replicated. Usually, the content popularity, storage capacity and bandwidth consumption should be taken into account.

Edge Server is deployed at the edge of core network, similar with the surrogate server in traditional CDN. It stores the "hot" content requested frequently by user nodes in the logically connected access network. P2P technology is used in core network in HCDN, allowing the edge servers can exchange content between each other. The edge server can get content from both central server and other edge servers in HCDN, while the surrogate servers can only get content from origin server in traditional CDN. On the other hand, the edge server provides indexing service for the logically connected user nodes. It manages the location information (indices) of content owned by each peer. Certainly, as mentioned in previous section, the indexing service can be separated from the edge server, and provided by a dedicated index server.

User Nodes are spread around access networks. In HCDN, the user node can strategically receive content from both the edge server and the other user nodes in same logical access network. If there are sufficient user nodes downloading the same content, user node mainly gets content from peers through P2P network, then the overload of edge server is decreased. When there are scarce user nodes downloading the identical content, user node mainly gets content from the edge server through CDN network, to provide the better QoS.

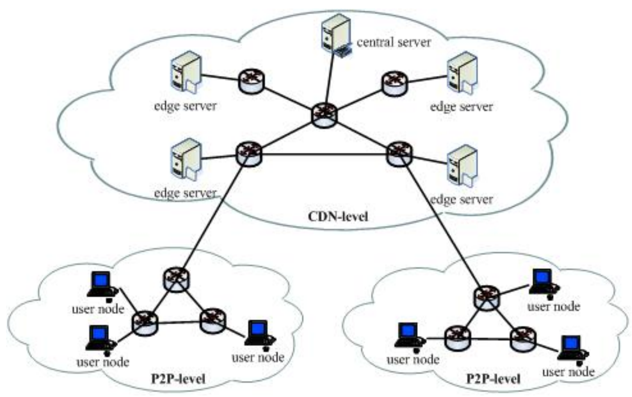

Fig. 2 The system topology of HCDN

In CDN-level core network, the edge server is a logical entity and it may consist of multiple physical servers or clusters. The request routing in traditional CDN, such as iterative or recursive scheme [13], can be also adopted in HCDN.

The P2P-level access network is an overlay network. The peers may be geographically separate and the access networks may be overlapped. In system implementation, the range of indexing service can be decided by request routing (e.g. intelligent DNS scheme) or selected manually by user nodes.

C. Content Distribution Operations

In HCDN, content distribution is divided into two stages: CDN-level and P2P-level stage. In the CDN-level, the content is placed from central server to a set of edge servers. In the P2P-level, the content is distributed from edge server to user nodes.

1) Content Distribution in CDN-level

In CDN-level stage, the parallel downloading is supported to improve distribution efficiency. The distributed content, a file or directory, is firstly deployed on the central server, and then placed to the specific edge servers. Which edge server should store the content is determined by the replica placement strategy. If the content has been placed to sufficient (can be denoted by threshold) edge servers, the central server can delete the content from its storage. To place content from central server to an edge server, the sessions are shown in Fig.3. After the request is received, a message is responded from central server to the target edge server, including content information and list of servers. The content information contains some key descriptions, such as unique identifier, size, and structure. The list of servers shows which edge server already stores the content. Then, the target edge server can send parallel requests to both central server and other edge servers, and get pieces of content concurrently.

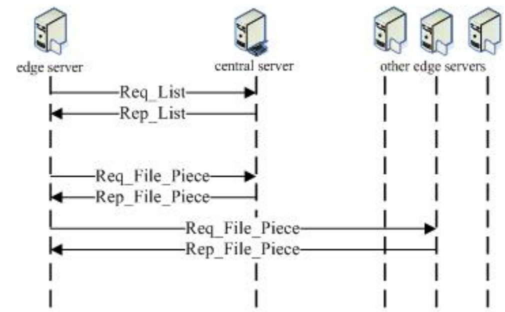

Fig. 3 The sessions of CDN-level in HCDN

The existing replica placement strategies [5], can still be used in the CDN-level content distribution. With these strategies, the content will be placed optimally. In order to achieve this, several factors are taken into account, such as cost of storage, bandwidth consumption, request frequency.

2) Content Distribution in P2P-level

Unlike edge servers, user nodes are dynamic and could online or offline at any time. In HCDN, the centralized schemes, such as the BitTorrent-like protocol [16], may be used in P2P-level content distribution. The edge server maintains an index table that includes content identifier, list of peers and local storage path. The item in list of peers has a lifetime which updated by peer periodically. When lifetime is zero, the item will be removed, and it means that the peer leaves from the specific content. The sessions are shown in Fig.4. Firstly, the user node sends a request which is routed to specific edge server by CDN routing scheme [13]. The edge server searches the index table by file identifier fetched from the request, and responds a list of peers. Then the user node can setup connections with the peer nodes. Furthermore, the user node also may concurrently connect to the edge server for downloading content.

The peer selection policies in P2P system [17][18][19] can also be used in P2P-level content distribution. In addition, there should be a principle that the downloading from user nodes is prior to from edge server. The edge server's capability should be more consumed by the user nodes which have scarce peers. This can be implemented by dynamically adjusting user nodes' downloading source.

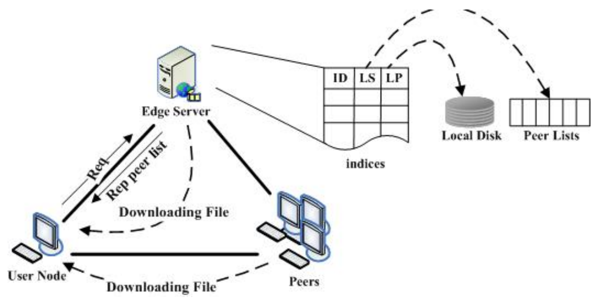

Fig. 4 The sessions of P2P-level in HCDN

IV. Performance Analysis

In this section, we will evaluate the proposed hybrid architecture, comparing with the traditional CDN and centralized P2P. To show the main differences, the performance analysis focuses on logical access network. Before describing our evaluation, we firstly give some assumptions about the analysis. We considered a homogenous environment in which each user node has an in-bound bandwidth of C_{in} and the bandwidth of edge server is denoted as B. We also assume that each user node downloads only one file at one time. The notations and definitions of the analysis are shown in Table I.

TABLE I
Notations and Definitions for the Analysis

Notation	Definition
B	Maximum outgoing bandwidth of the edge server
C_{in}	Maximum in-bound bandwidth of every user node
$x(f)$	Number of *seeds* for file *f*. Seeds are the participated user nodes that downloaded file completely
$y(f)$	Number of *non-seed peers* for file *f*. Non-seed peers are the user nodes that are downloading file
$s(f)$	Size of file *f*
u	Uploading speed of one user node
m	Number of files stored on the edge server
η	Effectiveness of the Peer-to-Peer sharing
d_s	Average distance from server to user node, by hop
d_p	Average distance between two user nodes, by hop

A. Service Capacity of System

The service capacity of the system is denoted by the maximum downloading capacity that can be provided by system. In traditional CDN's access network, the uploading service is only provided by the surrogate server, so it can be shown as:

$$SC_{CDN} = B \tag{1}$$

In centralized P2P architecture, the service capacity is provided by all peers sharing the identical content, including seed and non-seed. The factor $\eta(0\le\eta\le1)$ is used to show the effectiveness of uploading for a non-seed peer, which downloads from other peers at the same time, so the service capacity of P2P can be shown as:

$$SC_{P2P} = u\cdot\sum_{i=1}^{m}(x(f_i)+\eta\cdot y(f_i)) \tag{2}$$

For the HCDN architecture, the service is provided by the edge server and all participated peers, so we can obtain:

$$SC_{\text{HCDN}} = \text{B}+u\cdot\sum_{i=1}^{m}(x(f_i)+\eta\cdot y(f_i)) \tag{3}$$

B. File Downloading Speed

In traditional CDN architecture, the edge server's out-band capacity is shared by all the downloading user nodes. The downloading rate can be easily denoted as

$$speed_{CDN}(f) = \min(C_{in},\frac{1}{\sum_{i=1}^{m}y(f_i)}\cdot B) \tag{4}$$

In P2P architecture, the non-seed peers share the downloading service capacity of specific file, so the average downloading rate can be provided by P2P network is:

$$V_{P2P}(f) = \frac{u\cdot(x(f)+\eta\cdot y(f))}{y(f)} \tag{5}$$

Considering the limitation of maximum in-bound bandwidth, the user node's downloading rate can be got as:

$$speed_{P2P}(f) = \min(C_{in},V_{P2P}(f)) \tag{6}$$

In HCDN architecture, the requested bandwidth for edge server is the capacity excluded by the speed can be got from P2P-level network, and can be denoted:

$$R_{CDN}(f) = C_{in}-\min(C_{in},V_{P2P}) \tag{7}$$

The downloading rate of HCDN is composed of two parts, one is from the P2P-level network, and the other is from the CDN-level network. So, the formulation can be described as follows:

$$speed_{HCDN}(f) = \min(C_{in},speed_{P2P}(f)+\frac{R_{CDN}(f)}{\sum_{i=1}^{m}y(f_i)R_{CDN}(f_i)}\cdot B) \tag{8}$$

C. Overload of Server

For the edge server, its overload is the sum of all user nodes' request bandwidth, bounded by the maximum outgoing bandwidth. It can be denoted as:

$$O_{CDN} = \min(B,C_{in}\cdot\sum_{i=1}^{m}y(f_i)) \tag{9}$$

$$O_{HCDN} = \min(B,\sum_{i=1}^{m}y(f_i)R_{CDN}(f_i)) \tag{10}$$

D. Cost of Network Ttransmission

In CDN architecture, all content is got from the surrogate server, so the cost of network transmission can be presented as

$$Cost_{CDN} = d_s\cdot\sum_{i=1}^{m}y(f_i)s(f_i) \tag{11}$$

In P2P architecture, all content is received from other user nodes, so, the cost of network transmission is

$$Cost_{P2P} = d_p \cdot \sum_{i=1}^{m} y(f_i)s(f_i) \quad (12)$$

In HCDN architecture, user node retrieves content from both the edge server and the other peer concurrently, so the cost of network transmission can be calculated as

$$Cost_{HCDN} = d_p \cdot \sum_{i=1}^{m} \frac{speed_{P2P}(f_i)}{speed_{HCDN}(f_i)} s(f_i) + d_s \cdot \sum_{i=1}^{m} \frac{speed_{HCDN}(f_i) - speed_{P2P}(f_i)}{speed_{HCDN}(f_i)} s(f_i) \quad (13)$$

V. NUMERIC RESULT

Without the lost of general, we make some assumption to illustrate the numeric results. Firstly, we assume that there are N user nodes in the logical access network to download one file. Let user node's in-bound bandwidth is C_{in}=*500kb/s*, and the edge server's bandwidth for this file is *B=10mb/s*. We introduce the parameter p to denote the ratio of non-seed peer in all user nodes, that is, $x(f)=(1-p)N$, $y(f)=pN$. The user node's uploading speed is set to *u=100kb/s*, and effectiveness factor is set to $\eta=0.8$.

As shown in Fig.5, we can see the service capacity of HCDN is higher than that of traditional CDN and P2P, since the user nodes provide uploading service between each other. On the other hand, the P2P's advantages are outstanding as the number of participated user nodes grows up.

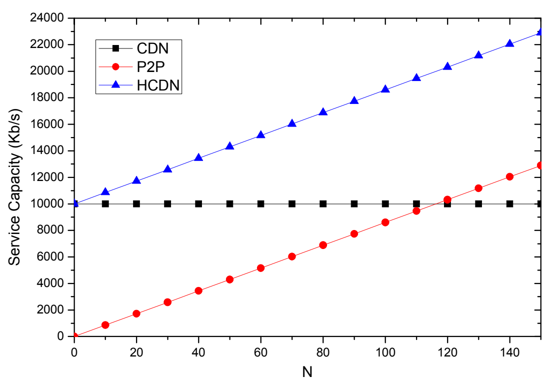

Fig. 5 The service capacity of CDN, P2P, and HCDN. (p=0.7)

In Fig.6, when the number of user nodes increases, the downloading speed of CDN decreases notably. On the contrary, the P2P's downloading speed doesn't degrade when N increases. The smaller p is, the higher downloading speed can be got in P2P, because the more seed peers can provide uploading service without downloading. To HCDN architecture, it is presented that significant improvement is achieved.

As shown in Fig.7, the overload of server in HCDN is much smaller than that in CDN. The more seed peers appear in network, the more advantages can be obtained.

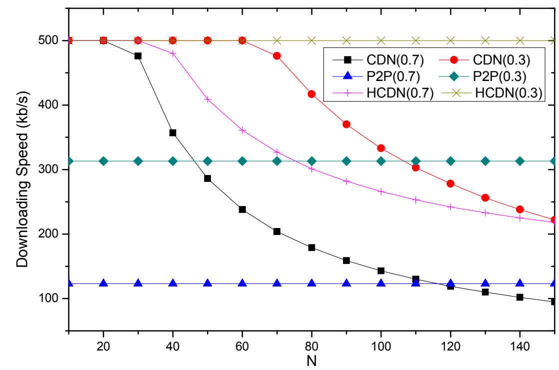

Fig.6 Downloading speed of CDN, P2P and HCDN with p=0.7 and 0.3

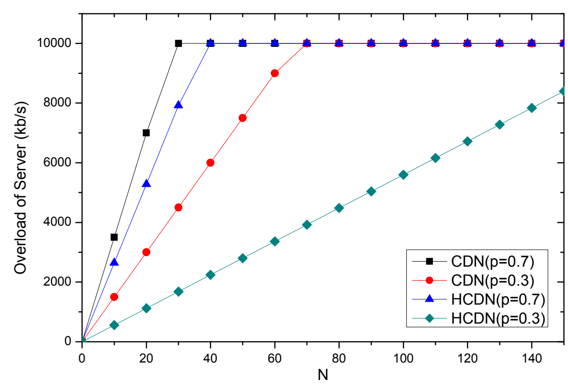

Fig.7 The overload of server in CDN, P2P and HCDN

As shown in Fig.8, the cost of network transmission in HCDN is much smaller than that in CDN, when $d_s>d_p$. With the growing number of participated user nodes, the cost of HCDN is close to that of P2P, since the content transmitted from P2P network increases rapidly.

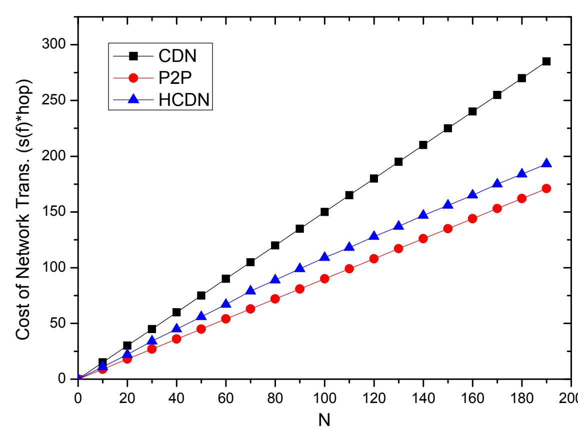

Fig.8 The cost of network transmission in CDN, P2P and HCDN ($p=0.3$, $d_p=3$, $d_s=5$)

VI. Conclusion

In this paper, we propose the HCDN, two-level hybrid architecture for efficient content distribution, integrating the traditional CDN and centralized P2P. The weakness of both CDN and P2P can be notably avoided in HCDN. As the analytical results show, compared with the traditional CDN and centralized P2P, the hybrid architecture can improve the content downloading speed and system service capacity as well as reduce the overload of server and the cost of network transmission.

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