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Efficient Large-scale Content Distribution with Combination of CDN and P2P Networks

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Abstract

With the growth of the Internet over the last decade, a key challenge for Internet infrastructure has been delivering increasingly large-scale content to a growing user population. CDN and P2P are two dominant technologies to improve distribution effectiveness. CDN may reduce the user-perceived latency, but it has shortage of expensive deployment. P2P can decrease the deployment cost, while it is of weakness to assure QoS when there are insufficient peers.

In this paper, we present a hybrid content distribution network (HCDN) integrating complementary advantages of CDN and P2P, which is used to improve efficiency of large-scale content distribution. To achieve in-depth understanding of HCDN's effectiveness, we carry out a detailed performance evaluation based on deterministic fluid model. We also provide numeric results of HCDN, conventional CDN and pure P2P. Some performance metrics are taken into account in our analysis, such as the evolution of the number of seeds and downloaders, the service capacity of system and the average downloading time.

1. Introduction

With the growth of the Internet in the span of a few years, a key challenge for Internet infrastructure has been delivering increasingly large-scale content of different types and origin to a growing user population. CDN (content delivery network) [1] and P2P (Peer-to-Peer) [2][3] are extensively applied to improve effectiveness of content distribution in this area. In CDN architecture, the content is disseminated strategically from origin server to a set of surrogates which are deployed across the wide-area Internet. Due to access content from closer surrogate, the client-perceived latency is reduced and the overload of origin server is decreased. However, there are some problems in CDN, for example, the high cost of deployment and maintenance, and limited service capacity of one surrogate. In P2P architecture, peers behave as servers as well as clients. The file one peer downloads is often made available for uploading to other peers. Since the content is exchanged between clients each other, the system scalability is improved and the deployment cost is reduced. But, there are also some limitations in P2P architecture, for example, the limited computational resource of one peer, the instability of dynamic peers, and the low performance of insufficient participated peers.

As can be seen, CDN and P2P have highly complementary advantages. In our previous work [4], we have proposed hybrid content distribution network (HCDN) to combine advantages of CDN and P2P to make up their own weakness. In this paper, we focus on the efficiency of HCDN based on in-depth performance analysis.

The remainder of this paper is organized as follows. The related work is summarized in section 2. The network model of HCDN is described in section 3. We present the detailed performance evaluation in section 4, and show the numeric results in section 5, comparing with conventional CDN and P2P. Finally, we also draw a conclusion in section 6.

2. Related Work

In the last decade, there has been a considerable amount of research work on content distribution in traditional CDN [1] and pure P2P network [2]. Limited to the length of the article, we will not describe the details of them, and only focus on the combination of CDN and P2P.

As far as we know, the integration of CDN and P2P is still at the preliminary stage, and there are only a few research work concentrated on it. [5] and [6] have proposed a PM-CDN (P2P-based architecture Multimedia CDN) and DCDN (Distributed Content Delivery Network), respectively. However, in these schemes, P2P architecture is only used in CDN network to support that the surrogates can directly exchange content. CDN-P2P hybrid architecture is adopted for streaming media in [7], but it mainly focuses on peer contribution strategy for media streaming. Some routing algorithms are shown in [8] and [9], but the hybrid architecture and its effectiveness are not mentioned. In our previous work [4], HCDN is proposed as two-level architecture to distribute large-scale content.

The inherent features make that it is difficult to model the P2P architecture. In [10] and [11], fluid model is used to analyze the BitTorrent-like network and P2P caching system, respectively. In [12], the Markov chain is adopted. In [13], a general model is proposed to describe the P2P network by queuing model.

In this paper, we use deterministic fluid model to illustrate the performance of HCDN. Differentiating from [10], our work is to analyze the hybrid architecture, and we compare it with conventional CDN and pure P2P network.

3. Hybrid Content Distribution Network

As shown in Fig.1(a), traditional CDN architecture can be described to a client/server model. 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 as 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-level and P2P-level. In backbone 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 and avoid the low performance of P2P when there are scarce peers in system.

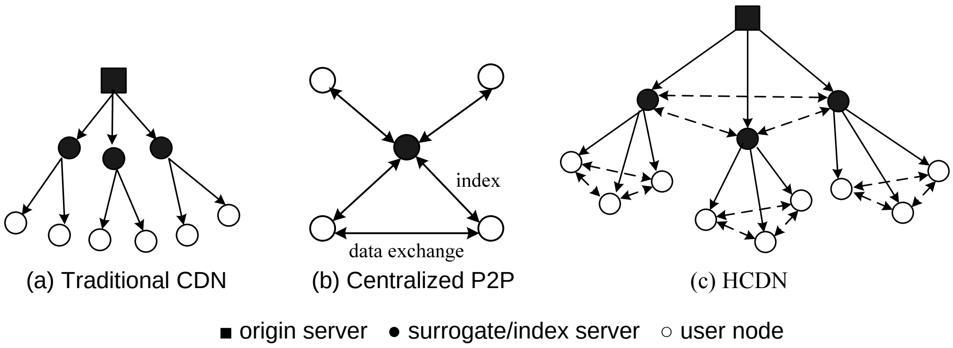


Figure 1. Models of CDN, P2P and HCDN

In CDN-level backbone network, the surrogate server is a logical entity and may consist of multiple physical servers or clusters. The request routing in traditional CDN, such as iterative or recursive scheme [6], can be also adopted in HCDN. The existing replica placement strategies [14] can still be used in the CDN-level content distribution.

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. The peer selection policies in P2P system [15] can also be used in P2P-level content distribution.

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.

4. Performance Evaluation

In this section, we will evaluate the performance of HCDN using deterministic fluid model which is proved to be effective for analysis of P2P network in [10]. The main goal of our work is to illustrate how efficient the HCDN can achieve, comparing with conventional CDN and pure P2P.

The notations and definitions of the analysis are shown in Table 1. The peers are classified into two categories: downloaders (the peers who only have a part of file) and seeds (the peers who have whole file but stay in system to allow other peers download from them).

Before describing our evaluation, we firstly give some assumptions about the analysis. We consider a homogenous environment in which each peer has the same in-bound and uploading bandwidth denoted with c and μ_p. We also assume that the arrival rate of requests follows a Poisson process. A downloader may leaves the system before it becomes a seed. We assume that the rate at which downloader departs from network follows exponentially distribution with mean $1/\alpha$. Similarly, we assume that each seed may stay in system for a certain time which is exponentially distribution with mean $1/\beta$. The factor ($0 \le \eta \le 1$) is used to show the uploading effectiveness of a downloaders.

Table 1. Notations and definitions

Notation	Definition
$x(t)$	Number of seeds at time t
$y(t)$	Number of downloaders at time t
F	Size of file
λ	Arrival rate of requests
μ_s	Outgoing bandwidth of surrogate server
μ_p	Uploading bandwidth of each peer
c	In-bound bandwidth of each peer
η	Effectiveness of the file sharing in P2P-level
α	The rate at which downloader abort the download
β	The rate at which seeds leave the system

4.1. Model description

Without lost of the general, we assume that the size of file is $F = 1$. In HCDN, if there is no constraint on the downloading bandwidth, the total uploading rate of system can be described as $\mu_p(x(t) + \eta y(t)) + \mu_s$. In this expression, $\mu_p(x(t) + \eta y(t))$ is contributed by P2P-level network and μ_s is provided by the surrogate server. If the constraint of downloading bandwidth is considered, it can be further got as $\min\{cy(t), \mu_p(x(t) + \eta y(t)) + \mu_s\}$. On the other hand, the rate of departures of aborted downloader can be gained as $\alpha y(t)$. So, in a fluid model, the output fluids of downloader will be given be $\min\{cy(t), \mu_p(x(t) + \eta y(t)) + \mu_s\} + \alpha y(t)$. Therefore, for HCDN, a deterministic fluid model of the number of seeds and downloaders can be shown as

$$\begin{cases} \dfrac{dx(t)}{dt} = \min\{cy(t), \mu_p(x(t) + \eta y(t)) + \mu_s\} - \beta x(t) \\ \dfrac{dy(t)}{dt} = \lambda - \min\{cy(t), \mu_p(x(t) + \eta y(t)) + \mu_s\} - \alpha y(t) \end{cases} \tag{1}$$

As to pure P2P network, it can be similarly expressed as following

$$\begin{cases} \dfrac{dx(t)}{dt} = \min\{cy(t), \mu_p(x(t) + \eta y(t))\} - \beta x(t) \\ \dfrac{dy(t)}{dt} = \lambda - \min\{cy(t), \mu_p(x(t) + \eta y(t))\} - \alpha y(t) \end{cases} \tag{2}$$

4.2. The number of seeds and downloaders

To consider the steady state, we let

$$\frac{dx(t)}{dt} = \frac{dy(t)}{dt} = 0$$

For HCDN:

According (1), we can obtain

$$\begin{cases} 0 = \min\{c\bar{y}, \mu_p(\bar{x} + \eta\bar{y}) + \mu_s\} - \beta\bar{x} \\ 0 = \lambda - \min\{c\bar{y}, \mu_p(\bar{x} + \eta\bar{y}) + \mu_s\} - \alpha\bar{y} \end{cases}$$

where $\bar{y}$ and $\bar{x}$ are the equilibrium value of $y(t)$ and $x(t)$ respectively. So, solving the equation, we have

$$\begin{cases} \bar{x} = \dfrac{c\lambda}{\beta(c+\alpha)} \\ \bar{y} = \dfrac{\lambda}{c+\alpha} \end{cases} \tag{3}$$

where $c\bar{y} \le \mu_p(\bar{x} + \eta\bar{y}) + \mu_s$, which means that the downloading bandwidth of downloaders is the constraint.

$$\begin{cases} \bar{x} = \dfrac{\eta\lambda\mu_p + \alpha\mu_s}{\eta\beta\mu_p - \alpha\mu_p + \alpha\beta} \\ \bar{y} = \dfrac{\beta\lambda - \lambda\mu_p - \beta\mu_s}{\eta\beta\mu_p + \alpha\beta - \alpha\mu_p} \end{cases} \tag{4}$$

where $c\bar{y} \ge \mu_p(\bar{x} + \eta\bar{y}) + \mu_s$, which means that the uploading bandwidth of system is the constraint.

For pure P2P network:

According (2), we can similarly get

$$\begin{cases} \bar{x} = \dfrac{c\lambda}{\beta(c+\alpha)} \\ \bar{y} = \dfrac{\lambda}{c+\alpha} \end{cases} \tag{5}$$

where $c\bar{y} \le \mu_p(\bar{x} + \eta\bar{y})$, and

$$\begin{cases} \bar{x} = \dfrac{\eta\lambda\mu_p}{\eta\beta\mu_p - \alpha\mu_p + \alpha\beta} \\ \bar{y} = \dfrac{\beta\lambda - \lambda\mu_p}{\eta\beta\mu_p + \alpha\beta - \alpha\mu_p} \end{cases} \tag{6}$$

where $c\bar{y} \ge \mu_p(\bar{x} + \eta\bar{y})$.

4.3. Service capacity of system

The service capacity of system is denoted by the maximum uploading capacity that can be provided by the system.

For HCDN, the uploading service is provided by the surrogate server and all participated peers, so we can get:

$$SC_{\mathrm{HCDN}} = \mu_s + u_p(x(t) + \eta y(t)) \tag{7}$$

For pure P2P network, the uploading service is provided by the all participated peers, so we have

$$SC_{\mathrm{P2P}} = u_p(x(t) + \eta y(t)) \tag{8}$$

Similarly, for conventional CDN, the uploading service is only provided by the surrogate server, so we get:

$$SC_{\mathrm{CDN}} = u_s \tag{9}$$

4.4. Average downloading time

For HCDN and pure P2P network:

To get the average downloading time in steady state, we use the Little's law to obtain

$$T = \frac{\frac{\lambda - \alpha\bar{y}}{\lambda}\bar{y}}{\lambda - \alpha\bar{y}} = \frac{1}{\lambda}\cdot\bar{y} \tag{10}$$

where T is the average downloading time, $\lambda - \alpha\bar{y}$ is average rate at which downloaders are completed, and $\frac{\lambda - \alpha\bar{y}}{\lambda}\bar{y}$ is the average number of downloaders which will become seeds.

Therefore, the average downloading time of HCDN can easily be got according (3), (4) and (10). We have

$$T_{HCDN} = \frac{1}{c+\alpha} \tag{11}$$

where $c\bar{y} \le \mu_p(\bar{x} + \eta\bar{y}) + \mu_s$, and

$$T_{HCDN} = \frac{1}{\lambda}\cdot\frac{\beta\lambda - \lambda\mu_p - \beta\mu_s}{\eta\beta\mu_p + \alpha\beta - \alpha\mu_p} \tag{12}$$

where $c\bar{y} \ge \mu_p(\bar{x} + \eta\bar{y}) + \mu_s$.

Similarly, the average downloading time of pure P2P network can also be obtained according (5), (6) and (10). We get

$$T_{P2P} = \frac{1}{c+\alpha} \tag{13}$$

where $c\bar{y} \le \mu_p(\bar{x} + \eta\bar{y})$, and

$$T_{P2P} = \frac{\beta - \mu_p}{\eta\beta\mu_p + \alpha\beta - \alpha\mu_p} \tag{14}$$

where $c\bar{y} \ge \mu_p(\bar{x} + \eta\bar{y})_s$.

For conventional CDN:

The system is a M/M/1 queuing model with following parameters

$$\begin{cases} \lambda_i = \lambda \\ \mu_i = \begin{cases} i \cdot c & 1 \le i \le m \\ \mu_s & i > m \end{cases} \end{cases} \tag{15}$$

where $m = \frac{\mu_s}{c}$, we have

$$P_i = \begin{cases} \left(\frac{1}{i!}\right)\left(\frac{\lambda}{c}\right)^i P_0 & 1 \le \mathrm{i} \le m \\ \left(\frac{1}{m!}\right)\left(\frac{\lambda}{c}\right)^m \left(\frac{\lambda}{\mu_s}\right)^{i-m} P_0 & \mathrm{i} > m \end{cases} \tag{16}$$

where $\sum P_i = 1$. Therefore, the average downloading time will be

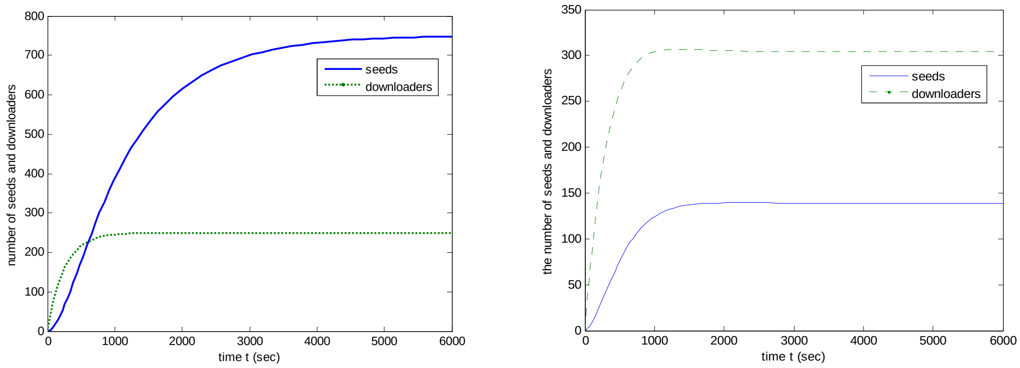
$$T_{CDN} = \frac{\sum iP_i}{\lambda} \tag{17}$$

5. Numerical Result

In our numerical analysis, we choose the basic parameters as: $\mu_p = 0.0015$, $\mu_s = 0.03$, $c = 0.003$, $\alpha = 0.001$, $\beta = 0.001$, $\eta = 1$ and $\lambda = 1$. In order to analyze the impacts of different factors, we will change the related parameters to show the result.

5.1. The number of seeds and downloaders

The basic case meets $c\bar{y} < \mu_p(\bar{x} + \eta\bar{y}) + \mu_s$ which means the downloading bandwidth is the bottle-neck. The evolution of the number of seeds and downloaders is shown in Fig.2(a). To study the case that the downloading bandwidth is not the constraint, we let $\beta = 0.005$ which meets $c\bar{y} > \mu_p(\bar{x} + \eta\bar{y}) + \mu_s$. The evolution is shown in Fig.2(b). We can find that the evolution includes two stages: exponential growth and steady stage.



(a) Downloading bandwidth is the bottle-neck   b) No constraint on downloading bandwidth

Figure 2. The evolution of the number of seeds and downloaders

To illustrate impact of the rate at which seeds leave the system, we change β from 0.003 to 0.012. In this case, the downloading bandwidth is not the constraint. As shown in Fig.3, the number of downloaders at steady state grows when the value of β increases. It means that there will be more downloaders waiting in queue. We also can find that the number of downloaders in HCDN is smaller than that in pure P2P network, since the surrogate server of HCDN contributes its uploading service.

To study the impact of the outgoing bandwidth of surrogate server, we change μ_s from 0 to 0.5. We also let $\beta = 0.005$ to make that the downloading bandwidth is not the constraint. As shown in Fig.4, the number of downloaders at steady state grows when the value of μ_s increases. This is the truth that high outgoing bandwidth of surrogate server can reduce the number of downloaders waiting in queue.

5.2. Service capacity of system

As shown in Fig.5, the service capacity of HCDN and pure P2P network increases when there are more peers in system. When the number of peers exceeds a certain value, the capacity of P2P will be larger than that of CDN.

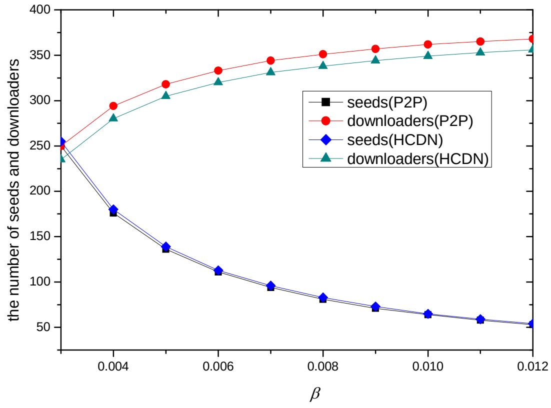


Figure 3. the number of seeds and downloads at steady state with different β

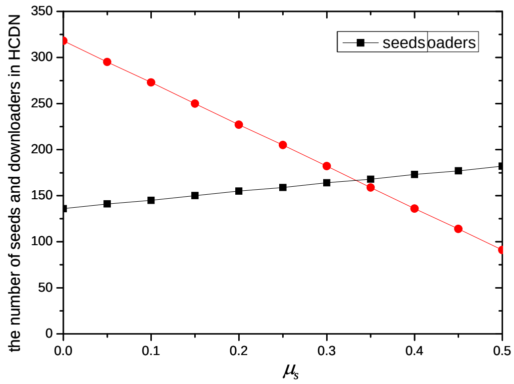


Figure 4. The number of seeds and downloaders at steady state with different μ_s

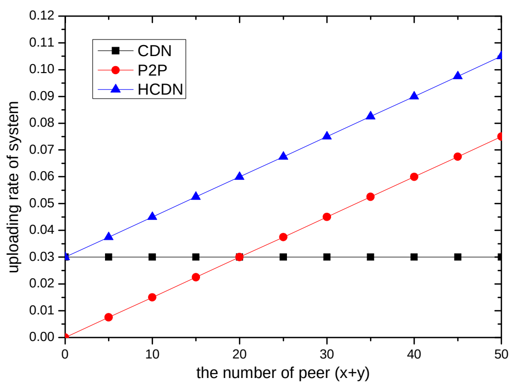


Figure 5. The service capacity of system

5.3. Average downloading time

To consider the average downloading time, we change λ from 0.027 to.0.0295 which is closed to $\mu_s = 0.03$. We also let $\beta = 0.001$ to make that the downloading bandwidth is the constraint. As shown in Fig.6, the average downloading time of CDN quickly grows when λ closed to μ_s. On the other hand, the average downloading time of HCDN and P2P is a constant according (11) and (13).

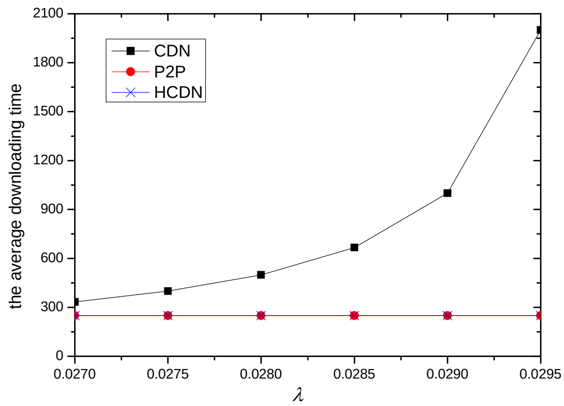


Figure 6 . The average downloading time when downloading bandwidth is the bottle-neck

To study the average downloading time when the downloading bandwidth is not the constraint, we let $\beta = 0.005$. We also change λ from 0 to 1. As shown in Fig.7, the average downloading time of HCDN is smaller than that of P2P. We also can see the average downloading time of P2P does not change when λ changes. This means that P2P architecture has good system scalability.

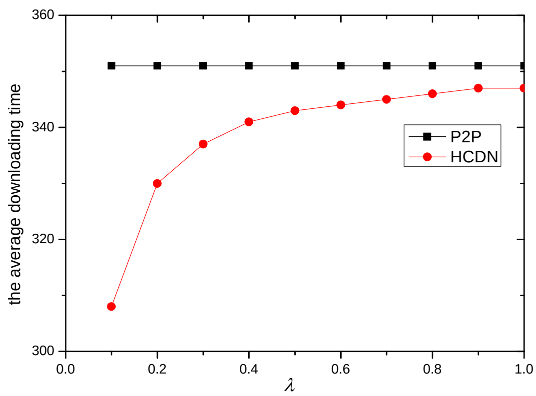


Figure 7. The average downloading time when no constraint on downloading bandwidth

6. Conclusion

In this paper, we have made an in-depth performance evaluation of HCDN, comparing with traditional CDN and pure P2P network. As is shown in our analysis and numerical results, we may draw a conclusion that the HCDN has many advantages on the average downloading time, service capacity and system scalability.

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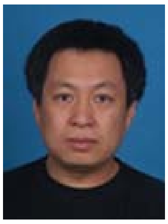

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