Deploying P2P Networks for Large-Scale Live Video-Streaming Service

Yun Tang, Jian-Guang Luo, Qian Zhang, Meng Zhang, and Shi-Qiang Yang

ABSTRACT

Peer-to-peer (P2P) networks have been adopted for Internet live video-streaming service, and several practical systems have been deployed in past years due to the inherent scalability and ease of deployment. However, most of these systems are commercial and proprietary, and hence little research was done in the area of characterizing practical system performance properties. In this article, we mainly present our experience on a practical P2P-based live video-streaming system called GridMedia, which was employed to broadcast live the Chinese Spring Festival Gala show over the Internet. Benefiting from two sets of flush-crowd traces with about 15,239 and 224,453 concurrent users in a 300 kb/s streaming session in 2005 and 2006, we perform a trace study to understand the service capacity, quality of streaming service, connection heterogeneity, user geographic distribution, and request and online duration characteristics. Our observations shed light on those systems and further improvements in the arena of large-scale live video-streaming service over the Internet.

INTRODUCTION

The increasing growth of the Internet and the digital content industry provides an interesting challenge that delivers media content in the form of live video streaming to a large group of users. From the viewpoint of system design in recent years, a rich body of literature discussed application layer multicast (ALM) or overlay multicast [1–4] to address the scalability problem without the requirement for either network infrastructure support in IP multicast or costly servers in CDN (content delivery network) architecture (e.g., see Akamai Technologies, Inc. at http://www.akamai.com/). In those approaches, the replicating and forwarding capabilities of end users rather than routers were utilized, and thereafter the peer-to-peer (P2P) concept emerged as it effectively explored the cooperative paradigm between individual participants. Each peer, which also can be called a user or node interchangeably, plays the role of both receiver and sender at the same time, and thus the system capacity is amplified by hundreds or thousands at a time. As the most likely means to provide group communication with ease of deployment and low cost, P2P first won its popularity in file-sharing applications such as BitTorrent (http://bittorrent.com/). In the last two years, many commercial P2P-based live-streaming systems were designed and implemented to provide live TV programs over the Internet including PPLive (http://www.pplive.com/) and CoolStreaming [5], to name two.

At the measurement study side, the universal recognition that it was critical to improve the performance of existing systems and protocols, with the understanding of practical service experiences, motivated prolific areas of research, which essentially came in two flavors. The first category of work commonly examined server workload, user characteristics, and streaming performance of client/server (C/S) or CDN-based live video-streaming service [6, 7]. The other category [8] analyzed P2P traffic, system capacity, and message protocols of P2P file sharing or voice over IP applications. However, little research was performed in the service traces of P2P-based live streaming in previous work, possibly due to the commercial and proprietary nature of those systems. Therefore, there is both a need and an opportunity to investigate corresponding issues and further enable new classes of next generation P2P networks.

In earlier studies [9], we also designed, implemented, and deployed a practical P2P-based live-streaming system called GridMedia. More importantly, it was adopted by CCTV (http://www.cctv.com), the largest TV station in China, to broadcast live the Chinese Spring Festive Gala show in 2005 and 2006, serving more than 500,000 and 1,800,000 person times respectively. Thus. it provided two sets of flush-crowd traces with about 15,239 and 224,453 concurrent users in a 300 kb/s streaming session in two years. In this article, we aim to offer an insightful understanding of the practical system performance properties of a P2P-based live-streaming system, comprising population evolution, quality of streaming service, connection heterogeneity, user geographic distribution, and request and online duration characteristics. Through a trace study, we made the following main observations:

- Our experiences demonstrated that P2P networks were becoming more global, more reliable, and achieved the expected success in the arena of large-scale live-streaming service.

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- Nearly 60 percent of users were behind various kinds of NAT (network address translation) and an effective NAT traversal scheme was vital in a practical P2P-based live-streaming system.
- The DSL users with asymmetric and limited upload capacity were able to obtain good quality of service, even if they could only contribute fewer bandwidth resources.
- There was a statistically positive correlation between the elapsed online duration and the expected remaining online time, which could be potentially exploited to improve the system.
- The annual flush-crowd event introduced vast and concentrative requests in a short period, and it is worthwhile to take the high request rate into consideration when designing those systems.

The roadmap of this article is organized as follows. We provide a brief overview of GridMedia, consisting of the overlay architecture and streaming protocol. We present the deployment settings and trace study methodologies, followed by the system performance properties. We then end this article with discussions.

Overview of GridMedia

In general, a practical P2P-based live-streaming system consists of two major parts: one is overlay construction, which takes charge of establishing relationships among peers according to different system-specific requirements; the other is streaming scheduling, which deals with how the video packets transmit along the peer pair in the networks. In view of a highly dynamic environment, that is, high churn rate in the peer community and a large number of simultaneous users, most successful systems commonly adopted gossip-based [10] unstructured overlay to accommodate requests from end users. In a typical gossip-based overlay structure, each peer maintains part of the members that are currently active and then selects a couple of them as neighbors to build bi-directional connections for data and message exchange. By this means, all peers self-organize into an overlay in a gossip fashion. Bearing high similarities to BitTorrent, the data-driven streaming protocol [5] was proposed for the gossip-based overlay to retrieve video content. It enabled each peer to retrieve the required data from neighbors with respect to explicit notification of data availability. In the design philosophy of GridMedia, which achieved success in large-scale deployment, we also adopted the prevalent gossip-based overlay structure and improved the pull mechanism in data-driven scheduling by a more efficient *push + pull* mechanism to achieve lower delivery latency [9]. In the following section, we briefly describe the overlay construction process and packet streaming scheduling.

Overlay Construction

In GridMedia, a streaming server acts as the source root. It takes the responsibility for streaming TV signals or recorded video files at a constant rate, for example, 300–500 kb/s in a general case, and 600 kb/s or higher for high definition contents. The video is divided into multiple segments and originates from the source root to all peers. A well-known rendezvous point (RP) in GridMedia consists of the content information, IP address, and service port of a streaming server. The major role of RP is to assist a requesting peer to join the existing overlay, to maintain a random part of active participants, and sometimes to act as a network monitor, if required. Note that according to various service scales, the streaming server and RP could be a cluster of multiple-dedicated machines with a load balance mechanism to avoid single point-of-failure.

The first-time user of GridMedia is asked to download the free client software from the Web site (http://www.gridmedia.com.cn). After installation, each peer selects one interested channel on the list of available channels, either on the Web site or in the tray icon of the client software that is updated at every launch. The join request of the new participant is sent to the RP, where the system accordingly returns the peer with the global synchronization time at RP and a candidate list of several peers already in the channel with their IP addresses and ports. The size of the candidate list is configurable and generally is 50 in GridMedia. Then the requesting peer measures the round-trip time (RTT) of each one in the candidate list and selects a subset (5 in GridMedia) with minimum RTT values as the first half of its neighbors. The second half of neighbors is randomly chosen from the rest of the candidate list, aiming to avoid the occurrence of overlay division. The join process succeeds when the peer establishes connections to those neighbors. To this end, each peer is provided with an initial membership list and a neighborship list. As mentioned, each peer maintains and updates these two lists with the evolution of the whole overlay.

Each item in the membership list represents an active node in the same channel. In GridMedia, we use *life-time* to denote the elapsed time from when a previous message was received from a peer on the membership list. After the life-time of one peer exceeds a predefined threshold (e.g., 60 seconds), it is regarded as failed and then removed from the membership list. The updated membership information is periodically exchanged between neighbors to refine the respective local membership lists. In addition to the unexpected failure, after a peer quits, it notifies all of its neighbors, and the quit message is flooded within certain hops of neighbors in GridMedia to trigger corresponding update operations to membership lists. The purpose of a membership list is to ensure that each peer evenly shares the burden of overlay construction by maintaining only a fraction of active nodes, and more importantly, to offer inherent resilience to high churn rates in a peer community with the benefit of randomness.

The chief task of membership lists in GridMedia is to exchange overlay information and video segments between neighbors. In addition to the small volume of update messages about membership lists, a large volume of video segments transmits along peer-pairs to the whole community in accordance with a specified

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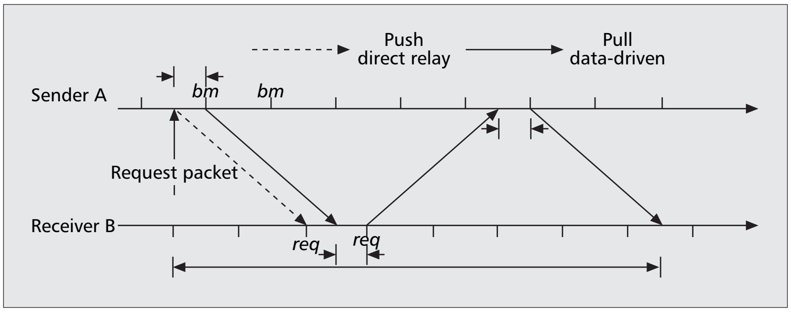


■ **Figure 1.** *Comparative delay of one packet using push and pull method.*

streaming protocol, which is discussed in the next subsection. During the live-streaming process, GridMedia forces each peer to periodically evaluate the bi-directional traffic with its neighbors. If the evaluated traffic quantity with a specific peer in one interval (e.g., 5 seconds) is less than the predefined threshold, this "poor" peer is discarded. In turn, a new one is selected from the membership list as the substitute. As a common circumstance in autonomous overlay networks, if one or more neighbors quit or fail, peers also probe the membership list to find new neighbors.

STREAMING SCHEDULING

Most streaming applications on the Internet are playback application, that is, the streamed data is first buffered at the receiver before playback begins again. The size of the buffer and its rate of drainage and replenishment determine the smoothness of the playback. In GridMedia, a streaming scheduler component takes responsibility for exchanging video segments with available neighbors. On the receiver side in P2P networks, it subscribes the demanding segments from neighbors. On the sender side, it offers the data in possession to others on request. Therefore, a data-driven streaming protocol involves a buffer to store a few minutes of segments within a sliding window, as well as a buffer map [5, 9] to denote the segment availability in the buffer of each peer. A buffer map generally has three fields: the maximum sequence number of the buffer map, the length, and a bit vector representing whether the packets with a corresponding sequence number is currently in the buffer. Each peer periodically exchanges buffer maps of video segments with its neighbors and then retrieves the absent segments from those who respond and own the segments.

Considering that the pull mechanism in data-driven streaming protocol essentially provides robustness for video segment transmission under highly dynamic network conditions, GridMedia adopted it as the basis of the streaming scheduling mechanism: each peer deploys a data-driven pull mechanism as a start up to request packets from its neighbors. However, in the process of steady transmission, this pull mechanism brings tremendous latency from source to each peer, that is, a huge delay between the sampling time at the server and the playback time at the users. Before proceeding, consider Fig. 1 as a running example. Observe that the data-driven streaming protocol in essence introduces the transmission time of the buffer map and the explicit request for absent segments, as well as the waiting time for generating the exchanged information. More seriously, those delays aggregate along hop by hop. In contrast, the push mechanism directly relays segments without an explicit request, resulting in lower transmission delay but potentially suffering from the unexpected failure of a link or peer. Therefore, the trade-off within these two mechanisms motivated us to leverage their advantages in the streaming scheduling in GridMedia as described as follows.

After the initial pull mechanism for start up, we enforce each peer to push a segment to its neighbors as soon as it arrives. Based on the traffic pattern in a previous interval, a roulette wheel selection scheme is employed to allocate the transmission rate and segments in the next time interval among multiple neighbors. In this sense, the pull mechanism in the first interval substantially guides an implicit line for subsequent rate and segment allocation. Furthermore, the pull mechanism is recalled when packet loss occurs during transmission, owing to either the unreliability of the network link or the failure of neighbors. The experiments at PlanetLab (http://www.planet-lab.org) demonstrated that the push + pull streaming mechanism in GridMedia achieved lower transmission delay than with the data-driven streaming protocol. For the live-streaming application, the buffer is replenished by the scheduler with a push + pull mechanism from neighbor peers and then drained by the player to decode and display.

DEPLOYMENT EXPERIENCE

As a scalable and cost-effective alternative to C/S and CDN-based approaches, GridMedia was adopted by CCTV to broadcast live the Chinese Spring Festival Gala show in 2005 and 2006 over the global Internet. The annual flush-crowd event enabled GridMedia to serve a significantly expanding population of concurrent users in two deployments and a high request rate in a four-hour event. In the following section, we first clarify the deployment settings and trace the study methodologies for ease of discussion. Then we present system performance properties in terms of service capacity, connective heterogeneity, and user geographic distribution, as well as online duration and request characteristics through a trace study.

DEPLOYMENT SETTINGS

Recall that the streaming server is the source root of the system. In a practical deployment, the TV signals are compressed and encoded in the TV station, and real time is pushed to the streaming server through a 2Mb/s fiber connection. The encoding and streaming rate is about 300 kb/s. The streaming server was equipped with Dual Core Xeon Server, 1 GB RAM, and RedHat Enterprise Service 3.1. It was located in the China Telecom Internet Data Center with 1 Gb/s uploading capacity.

In the first deployment in 2005, we set the maximum connections to the streaming server to 200, indicating that only 200 peers could obtain contents directly from the server. Thus, the workload on the streaming server was roughly 60 Mb/s. In the second deployment in 2006, facing the fact that such applications became more popular on the Internet, we increased the maximum connections to 800, that is, in total 240 Mb/s outgoing bandwidth on the server side.

Trace Study Methodology

The annual Spring Festival Gala show commonly begins at 8:00 p.m. and ends at about 12:30 a.m. the next morning. Therefore, in following statistical analysis, we focus on service traces from 7:30 p.m. to 1:30 a.m. on Feb. 8, 2005 and Jan. 28, 2006. Before proceeding to the system performance properties, we first clarify the trace study methodology in terms of user heterogeneity, quality of streaming service, and user characteristics. For user geographic distribution, we roughly map users into different countries with respect to their IP addresses and public IP database. For the connection heterogeneity issue, we identify NAT users by their different reported and displayed IP addresses in the traces. However, it is not a trivial task to determine a DSL connection without complex probing or measurement mechanisms. So we simply leverage the fact that most DSL users in China have two IP addresses with one 169.254.*.* to estimate a minimum percentage of DSL users. We further calculate the average streaming rate in terms of incoming and outgoing traffic every five minutes for those DSL users in China. To evaluate the quality of live-streaming service, we refer to the *delivery ratio* metric, which is the ratio of packets arriving before the playback deadline to the total packets and provide an average delivery ratio of end users. In this article, we mainly investigate the user online duration and request rate as the representative user characteristics in P2P networks. For user online duration, we retrieve from the traces the number of users every 10 seconds, the cumulative number and percentage of users, and the average remaining online time. For the request rate, we record the number of requests received by the RP every 30 seconds. We also classify the traces along the dimension of the year and user distribution to make a comparative study.

System Performance Properties

Service Capacity — During live broadcasting in February 2005, there were in total 500,000 person times from approximately 66 countries that subscribed to the service. The peak number of the concurrent users achieved was 15,239. In the second deployment, more than 1,800,000 person times from 69 countries logged in the service traces. The maximum concurrent users reached its peak at 224,453. Figure 2 shows the population evolution of concurrent users over time in two years.

It is easy to determine in Fig. 2 that P2P networks enabled 76 times (that is, 15,239/200≈76) in 2005 and more than 280 times (224,453/800≈280) in 2006 in terms of capacity amplification to bounded server outgoing bandwidth, respectively. The aggregate bit rate within one overlay in 2006 was in the vicinity of 67 Gb/s, which was a more exciting experience than that in [11]. For this four-hour flush-crowd event, we also notice that both of the peaks of

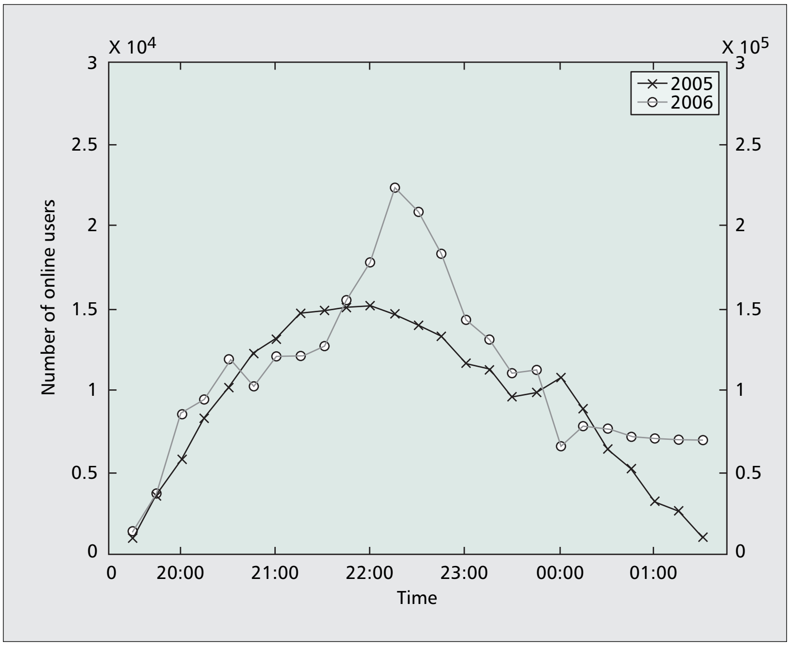


Figure 2. *Population evolution of concurrent online users in 2005 and 2006.*

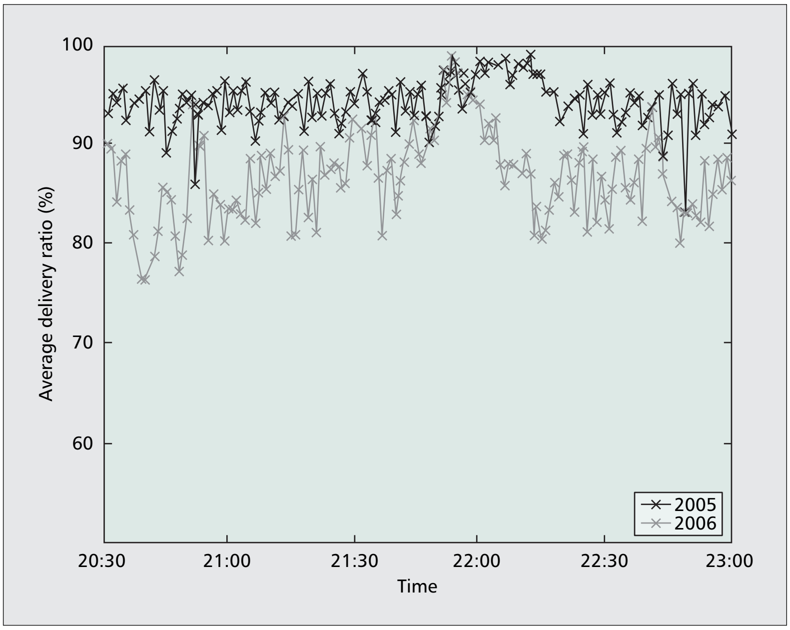


Figure 3. *Quality of streaming service in terms of average delivery ratio.*

concurrent users in P2P networks appeared in the middle of the show, at around 10 p.m. (21:57 in 2005 and 22:12 in 2006). Both populations showed a sharply descending trend at 23:30, which was near the end of the show. To evaluate the quality of streaming service from the perspective of end users, we further calculated the average delivery ratio in each year and drew the result during the steady process between 20:30 and 23:00 in Fig. 3 as an example. Note that both curves showed a continuous and dramatic fluctuation due to the high dynamics of underlying network conditions and peer community. However, the increased service capacity in 2006 actually brought higher quality of service (QoS) than that in 2005. We believe that the increasing popularity of a P2P-based live video-streaming system and a comfortable streaming quality of service demonstrated that the service could scale to reliably support a large number of users.

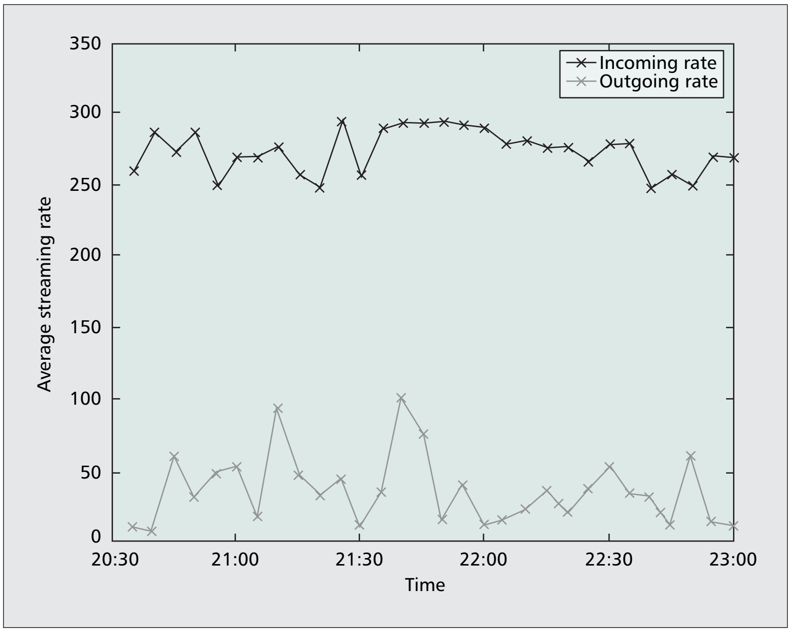
User Geographic Distribution — In reality, P2P networks, in general, are characterized by peers belonging to different administrative domains and connection types. Table 1 depicts the percentage of users in different geographic locations according to the IP addresses of end users. Because the annual Spring Festival Gala show is a famous Chinese celebration and GridMedia is deployed mainly in China, 78 percent of users in 2005 and 79.2 percent of users in 2006 were from China. There also were many users in other countries, for example, 3.96 percent in 2005 and 3.52 percent in 2006 from the United States and 4.02 percent and 2.92 percent users from Canada in the two years. In total, a majority of users in East Asia were from China and Japan, each constituting 80.2 percent and 81.8 percent in each year. The users in North America mainly came from the United States and Canada. They constituted 7.96 percent and 6.44 percent of total users.

Connection Heterogeneity — We also performed a statistical study of the connection heterogeneity. About 60.8 percent of users in 2005 were behind different kinds of NAT while at least 16.0 percent of users (in China) accessed the Internet via DSL connections. In 2006, the percentage of users behind NAT was a bit lower than that in 2005, about 59.2 percent, while there were at least 14.2 percent DSL users (in China). There was not much difference between the NAT percentage of users in China and that of users out of China in 2006, both of which were around 60 percent. However, it is worthwhile to note that nearly 60 percent of users in practical service traces were behind NAT, and an effective NAT traversal scheme should thus be carefully considered in the system design of P2P-based live-streaming applications.

Having isolated DSL users in China, we examine the average streaming rate per five minutes in terms of incoming and uploading traffic. As shown in Fig. 4, DSL users generally provided outgoing service at quite a low rate while they could obtain streams at an encoding rate. It is important and interesting to observe that DSL users could receive streamed contents at an average rate approximately equal to the encoding rate. This optimistic observation is attributed mainly to the altruistic contribution from other peers who act as server-like traffic amplifiers.

	2005		2006	
East Asia	China	Japan	China	Japan
	78.0%	2.86%	79.2%	2.58%
North America	United States	Canada	United States	Canada
	3.96%	4.02%	3.52%	2.92%

■ **Table 1.** *User geographic distribution (percentage of all users).*



■ **Figure 4.** *Average streaming rate of DSL users in China.*

Online Duration Characteristics — In addition to the heterogeneity of users, another characteristic that distinguishes P2P networks is that each peer, representing an end user, could join and leave the system frequently and continuously, resulting in a high dynamic in overlay topology and peer neighborship. From this viewpoint, the stability of a peer community is intuitively one of most vital factors for global system performance, and thus we select the online duration to study the user behavior characteristics. Figure 5 comparatively shows the cumulative distribution function (CDF) of the peer online duration in two years respectively. Note that in 2005, nearly 50 percent of users spent less than 180 seconds, and about 18 percent of users kept active for more than 1800 seconds. In contrast, roughly 30 percent of users in 2006 left the system in 180 seconds, and more than 35 percent of users would like to enjoy the show for more than 1800 seconds. The universal recognition that the more users, the better the quality of service, is also demonstrated by the fact that the online duration increases with the population.

In particular, the frequent turnover of upstream peers poses a substantial challenge regarding comfortable playback quality for end users in streaming applications. We further examine the correlation between the elapse online duration and the expected remaining online time. We find that peers with longer online duration are expected to have a larger average of remaining online time, which could be exploited to guide the design of further improvements to existing systems, for instance, by taking the online duration information into consideration when designing overlay structure or selecting upstream peers.

Request Characteristics — As mentioned previously, the annual flush-crowd event had a high churn rate existing in the peer community. Here we explore the request rate as the representative metric to show the highly dynamic feature of P2P networks, and which actually indicates the workload upon the RP that responded for a peer join request. For ease of presentation, Fig. 6 shows the request rate per 30 seconds from 23:00 to 0:00 in 2005 and 2006. Observe that the average request rate always remained at a record of hundreds in 2005 and thousands in 2006. Occasionally, the request rate reached a peak beyond 3,700 in 2005 and 32,000 in 2006. The high request rate and sporadic flush-crowd essentially pose a great challenge to the reliability of the RP server and system. Therefore, in addition to the gossip-based unstructured overlay for accommodating high dynamic peer community, it is also of great importance to provide a more stable and robust RP, for example, a cluster of multiple servers, in the face of so many requests in such a short period.

REMARKS

In a short summary, we make the following key observations from the deployment experience and trace study:

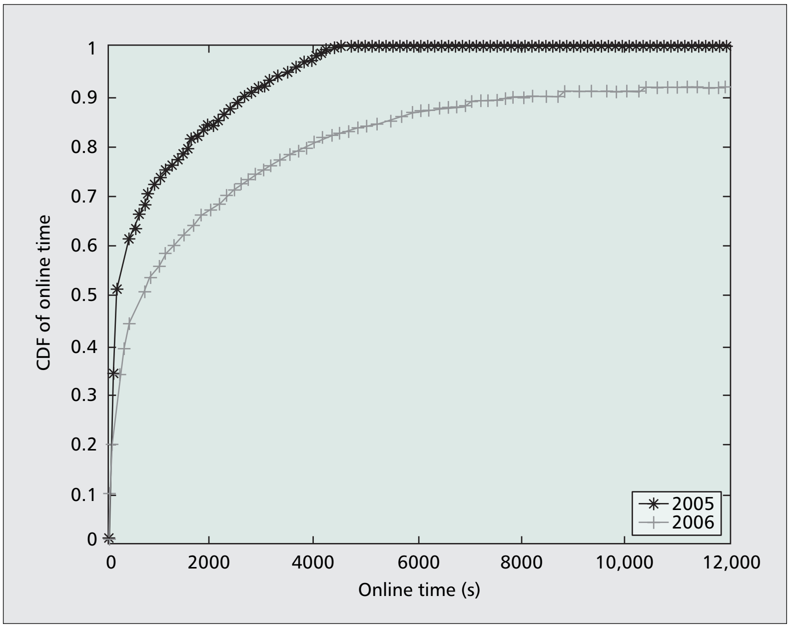
- Our experience demonstrates that P2P networks achieved the expected success in the arena of large-scale live-streaming service.
- There were nearly 60 percent NAT users in the practical systems, indicating that an effective NAT traversal scheme should be put in place. The DSL users with asymmetric and limited upload capacity were able to obtain good quality of service, even though they only could contribute fewer bandwidth resources.
- In terms of online duration, there was a statistically positive correlation between the elapsed online duration and expected remaining online time, which could be exploited to improve the system design by involving this characteristic.
- The flush-crowd event introduced vast and concentrative requests in a short period, which means that a robust and reliable RP should be considered carefully.

CONCLUSION

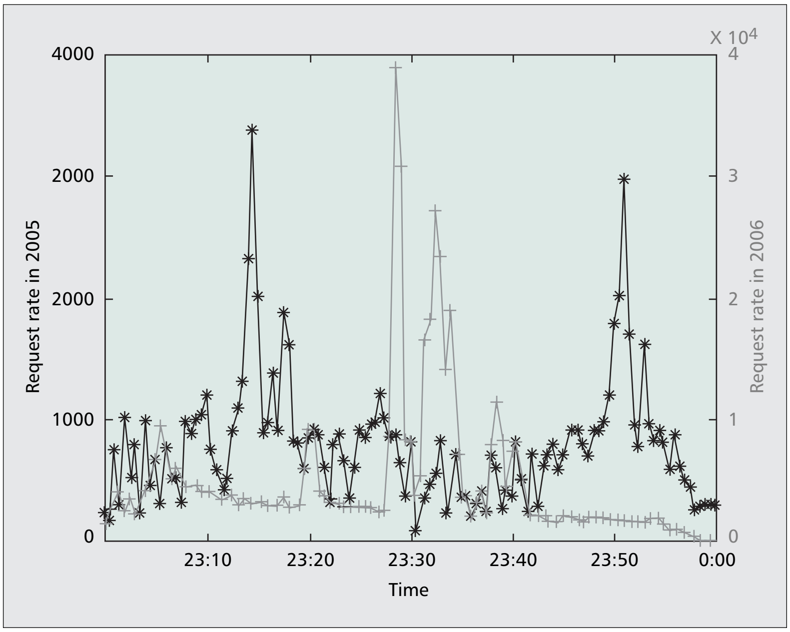
P2P-based live video systems emerged as one important Internet application that may significantly change both the traffic pattern in the underlying networks and the interplay between a huge volume of information and a large number end users. In this article, we mainly present the practical experience of GridMedia in broadcasting live the CCTV Spring Festival Gala show in 2005 and 2006, aiming to provide an insightful understanding of these kinds of systems from the perspective of system design and deployment. In these two deployments, GridMedia served more than 500,000 and 1,800,000 person times respectively. We studied the two sets of flush-crowd traces with about 15,239 and 224,453 concurrent users in a 300 kb/s streaming session in two years. More profoundly, the observations from the live broadcast of the annual flush-crowd event in two years essentially indicate that:

P2P networks achieved their success in the arena of large-scale live-streaming services. The increased system capacity and more stable quality of streaming service in 2006 than in 2005 demonstrated that P2P-based live-streaming systems were becoming more popular on the Internet. The universal recognition that the more users, the better quality of service, was verified and should motivate P2P networks to play a more important role in new classes of media distribution applications.

The user community exhibited strong heterogeneity in geographic distributions and connection types. More specifically, we observed that there were more than 60 percent users behind NAT and advocated that an effective NAT traversal scheme should be part of a practical P2P-based live-streaming system. However, we



■ **Figure 5.** *Cumulative distribution function of peer online duration in 2005 and 2006.*



■ **Figure 6.** *Request rate per 30 s in 2005 and 2006.*

P2P networks achieved their success in the arena of large-scale live-streaming services. The increased system capacity and more stable quality of streaming service in 2006 than in 2005 demonstrated that P2P-based live-streaming systems were becoming more popular.

also discovered that the DSL users in China, low contributors in the system to some extent, exploited the bandwidth resources and hence obtained streamed contents at an average rate approximately equal to the encoding rate. The synchronous nature of a live-streaming service, that is, all peers requesting the same contents, fundamentally facilitated the altruistic behaviors from other server-like traffic amplifiers.

There was a statistically positive correlation between the elapsed online duration and expected remaining online time. Considering that in streaming applications, the frequent turnover of upstream peers posed great challenges to smooth and continuous playback, it is important to exploit this statistical characteristic to further improve the streaming stability in a peer community, for instance, by involving peers with a larger online duration into the overlay structure design.

ACKNOWLEDGMENT

We are grateful to CCTV in China for helpful cooperation. We also would like to thank the anonymous reviewers and editors for valuable suggestions and detailed comments. This work was supported in part by the grant from HKUST under NRC06/07.EG01, NSF China under Grant no.60432030, no.60503063 and no. 60629203, and National Basic Research Program of China (973 Program) under Grant no. 2006CB303100.

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