Computer Networks 54 (2010) 13–27

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Measurement-based study on the relation between users' watching behavior and network sharing in P2P VoD systems ☆

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ARTICLE INFO

Article history:
Received 24 May 2008
Received in revised form 4 May 2009
Accepted 3 August 2009
Available online 25 August 2009
Responsible editor: H.S. Hassanein

Keywords:
P2P
VoD
File dissemination system
Peers' watching behavior
Network sharing

ABSTRACT

P2P-based Video on Demand (P2P VoD) systems can provide higher quality video services than P2P live systems. However, owing to the unavailability of open source codes, the characteristics of P2P VoD systems have not been fully explored. For this purpose, in this paper, we first implemented reverse engineering to the protocols of two most popular VoD systems used in China. Peers' watching behavior and network sharing were then studied through the measured buffer messages. Based on our study, we found that uploading-only peers were more than downloading peers, and smooth-watching peers were more than randomly-seeking peers in the current P2P VoD systems. This finding is significantly different from the existing P2P-based file dissemination systems and the results obtained in the previous work on VoD systems. Furthermore, this study revealed the relations between watching behavior and network sharing. It has been observed that randomly-seeking peers will provide more regular as well as rare chunks than smooth-watching peers. A simple mathematical model was established to analytically demonstrate the relation between the watching index (WI) distribution and network-sharing profile, and this relation was also validated by our measured data.

1. Introduction

Recently, new demands and technology have boosted up P2P-based Video on Demand (P2P VoD) streaming systems, after P2P-based live system became a popularly deployed platform 2 years ago. The VoD application provides more attractive features than live system, such as better interactive interface and controllable video time. Much work has been carried out on P2P live streaming systems. In contrast, P2P-based VoD system is a relatively new topic and still lacks in-depth exploration. In this paper, we will focus on the measurement and characterization of P2P-based VoD systems.

As an efficient volume data dissemination technology, P2P plays a key role in many contemporary applications. One of such applications is file downloading (e.g., BitTorrent (BT) [15]). Users who download the same file can help each other so that the server load is significantly reduced. Example applications include P2P live streaming (e.g., the system supported by a university project Coolstreaming [1], and many commercial systems such as PPLive [18]). Again, users who watch the same live video can help each other to alleviate the load on the server. In this case, the new challenge is to deliver each segment of video stream to every peer on time. As all peers watch the same part of the video stream at the same time, the same piece of data must be sent to every peer within a short time interval, and hence, the full cooperation among all the peers is the most important design criterion. Most recently, this service has promoted a new service, namely, P2P VoD. An analysis of the client–server VoD systems by Microsoft [11] showed that P2P-VoD systems could bring significant

☆ This work was supported by China NFSC 60672069, 60772043 and China 973 2007CB307101.
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doi:10.1016/j.comnet.2009.08.013

reduction in terms of server load. Since then, a number of P2P VoD systems have been deployed almost at the same time as reported by Microsoft [11]. Large viewer population has been attracted by these VoD systems. Like P2P streaming systems, these P2P VoD systems also deliver contents by streaming, but peers can watch different parts of a video at the same time, and the cooperation pattern among peers in P2P VoD system significantly differs from that in P2P live streaming system. To our knowledge, the problem of what is the best cooperation pattern and how peers can help each other effectively in such a P2P VoD system has not yet been investigated. In this paper, we have attempted to tackle this problem through measurement-based study.

Unlike traditional VoD systems, wherein video-content servers are the only data sources, in P2P systems, peers share video contents among themselves. With such a distributed P2P structure, the pressure on the content server and its access bandwidth would be largely relieved. The architecture of a P2P VoD streaming system is similar to that of a live system. Few servers (called trackers or seekers) are deployed to support a large number of audiences (called peers). Like P2P live streaming, the video data is also divided into chunks identified by continuously assigned sequence numbers. The sequence number is referred to as the chunk ID. However, the data were oriented by movie in a VoD system, instead of a channel in a live system. A channel may last for a very long period of time so that infinite IDs are needed to identify different contents on the channel. In contrast, a movie has limited size so that it requires only finite IDs to identify different chunks of its contents. On the other hand, the chunk size in P2P VoD system is about 2 M bytes, which is much larger than that in P2P live streaming system, and the chunk ID space for a movie in a VoD system is smaller than 200 in most VoD systems. Each peer in a P2P streaming system has a buffer for storing chunks. A buffer map (BM) is used to describe the chunks currently stored in the buffer. A BM consists of a sequence of $\{0,1\}$. More specifically, a value of 1 (0) at the ith bit position indicates that the chunk with identifier i is (is not) available in the buffer. Periodically, a peer advertises its BM to its neighbor peers, and also receives BM messages from its neighbors. Based on these messages, peers exchange chunks among themselves to fill their buffers. However, instead of saving a small window of streaming as in a P2P live system, a peer in a VoD system saves all the downloaded data into a larger memory cache and also the hard disk cache. Thus, the VoD peers can share all their data with others without limitation. Furthermore, the peers in a live system discard all their video data when terminating or exiting the system. In contrast, a peer in VoD system retains his/her video data in the hard disk cache. Thus, each VoD peer could be a "server" to serve the part of the movie that was ever cached. In a traditional server-based VoD system, multiple users may watch a movie at any given time such that the server has to supply different streaming to each user. Therefore, the server load and its access bandwidth will be proportional to the number of admitted users. However, this has scalability problem, which is solved in a P2P VoD system by chunking a movie and caching different chunks at peers.

Measurement is a key technique for evaluating the performance of a P2P VoD system. However, measuring a publicly deployed P2P VoD system is challenging. This is because all such systems today are proprietary, i.e., their source codes are not publicized and there are no specifications on the communications protocols used in these systems. Reverse engineering has to be used to guess how peers interact with each other as well as with trackers. In this paper, we have described our practices of the reverse engineering with regard to the protocols in PFSVOD [20] (the VoD software released by the PPLive company [18]) and PPStream VoD [21], which are the top two most-popular P2P VoD systems currently used in China. We have also shown how a crawler can be built based on the understanding of these protocols after reverse engineering. Finally, we have used collected data to study the characteristics of a P2P VoD system.

The most important finding of this paper is as follows: while "matching forward" is the main cooperation style in a P2P live streaming system, the "older peer helps newcomer" is the main cooperation style in a P2P VoD streaming system. We say "matching forward" in a P2P live streaming system because all peers are "crowded" together in exchanging the same piece of stream video at a time, then the next piece at the subsequent time. In contrast, only those peers who have watched the same piece of stream video can help a given peer watching this piece of video in a P2P VoD system. Thus, older watchers can help new watchers in data sharing. In summary, the cooperation in a P2P VoD system comes from the watching history of online peers. In our study, the watching history of peers is abstracted as the peer watching behavior, which represents the probability of watching a portion of a given video, and the peer-helping pattern is abstracted as network sharing, which represents the number of online peers who possess a given piece of video. Thus, we have concentrated on the relation between peer watching behavior and network sharing. The main findings of this paper are as follows:

(1) Unlike the existing large-scale P2P-based file dissemination systems, such as BT and live streaming systems, in a P2P VoD system, the majority of peers (more than two-thirds of them based on our measurements) are "seeders." These peers only provide data to others for data sharing without any downloading. As we have discussed earlier, this is the foundation of the cooperation among peers in a P2P VoD streaming system.

(2) A new method has been proposed to study the watching behavior of VoD users by using their BM information. By using this method, we were able to observe that
   (a) Most VoD users play a video successively and passively from the beginning.
   (b) VoD users rarely view a movie till the end. The total playing time is quite limited and tends to be short.
   (c) Noticeable VoD users play video by jumping, i.e., they watch some scenes while skipping some others.

(3) Unlike all the other P2P-based file dissemination systems, the sharing performance of a P2P-based VoD system depends on the watching behavior of the users. The jumping peers generally contribute more regular chunks and also rare chunks than those peers who watch a video successively and passively from the beginning.

(4) Peer's *watching index (WI)*, defined as the maximum chunk ID that a peer has in his/her sharing buffer, and chunk's *sharing profile*, defined as the number of online copies of a given chunk, are introduced to characterize peers' watching behavior and network-sharing characteristics, respectively. A simple mathematical model is established to analytically demonstrate the relation between the distribution of WI and sharing profile. In addition, this relation is also validated by the data collected from real network.

Related work: There have been many discussions on the technology and marketing of VoD since the first commercial VoD service was launched in Hong Kong around 1990. However, till date, large-scale server-based VoD system has not been deployed in public networks. Coolstreaming is the first deployed P2P-based live media system around 2003 [1]. After that, a numbers of P2P live streaming systems were successfully deployed around 2005. Consequently, measurement-based studies on these deployed systems were published since then (see [2–6]). The playing-back continuity and start-up latency are the main performance metrics of concern. Furthermore, passive sniffing and active crawling, as the two measuring technologies, have been applied to measure the existing P2P live streaming. Even though the measurement methods can be applied to measure the performance of a P2P-based VOD system, there are vital differences between live streaming and VoD streaming. In a live streaming environment, all peers may need the same piece of video at a short interval of time. The most important task for clients is to distribute the time-sensitive data as quickly as possible in a fully cooperated manner. This kind of cooperation is not observed in a VoD streaming environment, as different peers view different pieces of video at the same time. In this study, the cooperation in a VoD system is shown to be rooted to the watching history of other peers, instead of their current watching activities, as in a live system. Furthermore, users' interactive behaviors such as pausing and random jumping are allowed when they are subscribed to VoD services; however, live streaming systems do not provide these features. As a result, the viewpoint for studying a real P2P VoD system is essentially different from that for a P2P live streaming system.

Most of the existing works in the field of P2P VoD systems (see [7–10]) were carried out before the real deployment of such systems. Hence, those studies concentrated on the protocol design of topology and analysis of simulation results. As most newly emerged P2P VoD systems are a generalization of their respective original live systems, previously published literatures on live systems could be employed to study the VoD systems. Measurement-based studies on a P2P VoD system were reported in 2008 (see [11,12]). However, the systems studied [11,12] were not real VoD systems, as neither of them were deployed publicly or were openly applicable in large scale for Internet users. Furthermore, a single-video system was studied [11], in which a peer only redistributed a video that was watched currently. This was observed to be inconsistent with the typical working mode of today's P2P VoD system based on our measurement. Majority of the peers in the current system were observed to redistribute videos that they are not watching. Furthermore, both the earlier studies [11,12] investigated the problem of pre-fetching, which is a technique employed in the implementation of the system. However, in this paper, we have concentrated on the interaction between the users' watching behavior and network sharing, which is considered to be directly related to the cooperation philosophy behind the system.

The users' watching behavior on server-based VoD system has been studied earlier [13,14]. In the earlier studies [13,14], the data were collected from the log file of a centralized server, and only researchers with access to large video service providers were able to obtain this kind of data and carry out related studies. In contrast, in this paper, we have proposed a method to study the users' watching behavior directly from the collected peer buffer messages. Thus, any interested scholars could conduct such study easily with a network-connected PC. Furthermore, the watching behavior studied earlier [13,14] was not based on a group of cooperating users, as they would be in a P2P environment. The network condition and the transmission protocols used in earlier studies [13,14] were also different from those in a P2P network. Thus, whether the behavior reported earlier [13,14] would be applicable in a P2P environment is questionable. The watching behavior studied in this paper was directly from those peers who fetched the data from and redistribute video to other peers in a P2P environment. Their behavior was observed to be just a result of the system under study, and was also directly related to the data-sharing environment where they were working.

Intuitionally, environments are found to affect the human behavior. The environments provided by server-based and P2P-based VoD systems are quite different in many aspects. In a P2P-based VoD system, the restart time after a jump in watching is significantly longer than that in a server-based system. The frequency of random seeking is expected to be noticeably small in a P2P-based VoD system. In addition, besides the attractiveness of the content, the playback quality may also affect the duration of watching a movie. The data of a client in a server-based system are obtained directly from the server. The current load on the server determines the playback quality of each client. In contrast, the data of a peer in a P2P-based system come from other peers who have watched such a movie piece. Therefore, the watching behaviors of users in server-based and P2P-based systems are very likely to be different. To our knowledge, no study has been conducted to compare the differences in watching behaviors between these two types of systems. Our results in this paper reveal that the watching behavior in a P2P VoD system differs significantly from the previously reported behaviors. However, we did not concentrate solely on studying these differences.

Network sharing is always a major concern in a P2P-based file dissemination system, such as live streaming and BT systems [15–17]. It is believed that the sharing efficiency is directly related to the distribution of the available copies for each data piece. In an earlier study [16], a uniform distribution is assumed to deduce the network-sharing efficiency. In another study [17], the authors studied the live streaming system based on a BT-like architecture. A peer's uploading fraction has been derived under the same assumption of a uniform piece distributed among the neighbors. The assumption of the uniform distribution is based on the fact that all peers are only interested in a small window of data at a time, in a live system. Hence, a quick dissemination of those data will make the piece distributed in a nearly uniform manner.

In this paper, we have studied a different sharing mechanism that is designed for P2P-based VoD systems. Based on our measurement, the downloading peers in a P2P VoD system are observed to be significantly smaller than the uploading-only peers (the "seeders," as mentioned earlier). As the majority of the peers are "seeders," the piece copy distribution is mainly determined by the uploading-only peers. An uploading-only peer may not follow the pace of downloading peers to capture new pieces, and the distribution in available copies of different data pieces cannot be changed significantly along with the downloading progress of any given peer. Therefore, uniform distribution is no longer suitable for a P2P-based VoD environment. Since what an uploading-only peer has is the result of this peer's watching history, the peers' watching behavior will be a key factor to understand the sharing distribution in a P2P VoD system. In this paper, we have studied this problem and developed a simple mathematic model to establish the analytical relationship between watching behavior and share profile.

An earlier study [22] was published after the submission of this paper. It is the most in-depth study on practical design and measurement issues related to a real P2P VoD system so far. The authors [22] were apparently with the vendor of the measured system, which made the measurement relatively easy for them, as they had full access to all types of data. However, the method introduced in that study [22] may not be applicable to most researchers, and the results therein are not as objective as those drawn from the third parties. Moreover, the scope of that study [22] is much broader than that of this paper. Even though many generic performance factors were identified and calculated based on the measured data [22], an in-depth analysis on the cooperation mechanism in a P2P VoD system was absent.

This paper is organized as follows: in Section 2, a brief description of the P2P VoD system is provided along with the outline of our reverse engineering on the protocol and message format used in PFSVOD and PPStreamVoD. In Section 3, the analysis on watching behavior and sharing profile based on our measurement is provided. A simple mathematical model is developed to demonstrate the relation between WI and sharing profile. Finally, in Section 4, the summary and conclusion are presented.

2. P2P VoD systems and our measurement platform

2.1. Brief description of P2P VoD system

The P2P technology promotes the development of the new generation of streaming media system. Unlike traditional VoD systems where video content servers are the only data sources, in P2P systems, peers can share major percentage of the video contents among themselves. With such a distributed P2P structure, the pressure on the content server and its access bandwidth is largely relieved.

A typical P2P streaming system consists of live and VoD subsystems. It must be noted that the early versions basically only support the live program, until late 2007 or early 2008. Fig. 1 gives the basic architecture of a P2P streaming system. A more detailed description can be found in earlier studies [1–6]. There are many dramatic changes in the design philosophy between a P2P VoD system and a P2P live system, which are listed as follows:

(a) In a P2P live system, a peer saves the received data in a very limited-size memory. In a VoD system, a peer saves all the downloaded data in a larger memory cache as well as hard disk cache. Thus, a VoD peer can share all his/her data with others without limitation. When terminating or exiting the system, a peer in a live system discards all his/her video data. In contrast, a peer in VoD system may retain his/her video data in the hard disk cache. Several years ago, it was still questionable whether a user would like to contribute disk space in a system like VoD. However, recent practices show that the users do not mind in sharing more resources with others in return for better playback experience.
(b) P2P live system is a source-driven system, such that the server controls the content feeding rate. Thus, the seed server limits the peer's playback tempo. On the other hand, the P2P VoD system is a receiver-driven system such that the peers themselves control the tempo and no server synchronization is needed. As there exists no downloading window that may limit the data sharing, all peers can share all they have with others. Thus, a VoD user has more flexibility to choose different playback patterns.
(c) In early P2P live systems, most data were packaged in TCP. In contrast, in VoD systems, though nearly all of them support TCP and UDP transferring, more

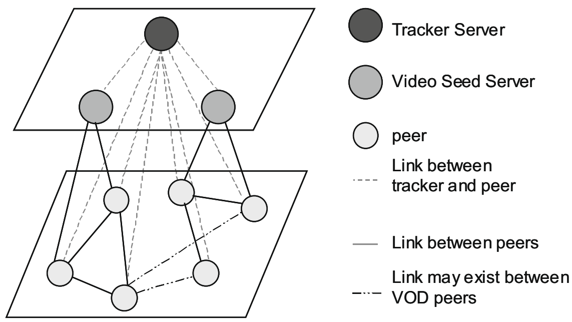

Fig. 1. Architecture of a P2P streaming system.

and more streaming systems have started to adopt UDP for data transferring (e.g., JOOST system [19]). In PFSVOD and PPStreamVoD, most of the messages are sent via UDP datagrams, which makes the reverse engineering easier to some extent.

2.2. Outline of our reverse engineering

Measurement is important in studying a VoD system. Reverse engineering is an inevitable step in developing measurement tools, because all P2P streaming systems so far are proprietary. Till date, there exist no open source codes or specification describing a streaming protocol in detail.

Two systems, PFSVOD and PPStreamVoD, are chosen in our work because they are the top two most popular P2P VoD systems used in China. Furthermore, all the packets in PFSVOD and PPStreamVoD are transmitted in plain text via UDP, which makes it relatively easier to guess how their protocols work. Our reverse engineering has been conducted in the following three stages:

At the first stage, by tracing a standard VoD client, we captured the interactive packets between the local VoD peer and others by using ethereal tool. Based on our experience on live systems, we included some types of basic packets in a VoD system, such as BM packet, data-piece request packet, data-piece response packet, and shakehand packet. We also assumed that each packet is a complete VoD protocol message, as it is delivered using UDP. We were able to figure out the rough protocol format by matching those traced packets with those known types of basic packets. However, there were still some details left unknown.

At the second stage, the traced data were fed into a dumping tool that can filter data into a text file with composed conditions, such as source IP/port, destination IP/port, and VoD protocol type. By inspecting the text file of different channels, many regular changes were found, which helped us to parse the protocol format in detail. Of course, there were still one-third irregular data. In this case, we guessed and tried it in the subsequent step and our experience knowledge worked. At last, we parsed about 99% PFSVOD protocol and 90% PPStreamVoD protocol, and after considering the network sharing of both PPLive and PPSteam, we chose PFSVOD as our measuring object.

In PFSVOD system, there are about 15 types of messages. Each type of message is encapsulated without any VoD protocol mark, to evade from the restrictions that the ISPs may enforce. Among the different types of messages, BM messages (Type 14) and peer list messages (Type 12) have been the most useful messages for us to measure and analyze the VoD system. Similar to its counterpart in P2P live system, within each BM message, there is a sequence of bytes named BM that indicate what the peer has cached and is willing to sharing. The BM length is different for different movies. However, each bit in the BM stands for a fixed-sized data chunk of 1920 KB length for almost all the movies.

At the third stage, we analyzed the time sequences of PFSVOD protocol messages. Some events in the time sequence were obvious, such as data request and response, while some were not. In the latter case, we guessed and tried different composed events until a correct sequence. Ultimately, all the events were acquired.

In general, when a peer starts a new channel, he/she first notifies the tracker that he/she is ready to share the contents with others and wants to get peers at the same channel. Subsequently, the tracker will send a peer list to the peer, and after that, the peer sends shakehand message to other peers as well as the tracker. Shortly after that, other peers will send BM messages to the peer, and at last, the peer starts to upload and/or downloads data pieces to/from others. It is worthy mentioning that if a peer does not want to serve as a "server," then he/she should not notify the tracker that he/she is ready to share the contents with others when he/she starts up. This is useful for us to implement a crawler.

2.3. Crawler and dataset

A PFSVOD crawler is designed with the above-mentioned knowledge. It runs on top of Microsoft Windows and is capable of probing multi-channels with each channel having up to 2000 peers at the same time. The basic interactive flow adopted in our crawler is shown in Fig. 2. When running, the crawler first reads a channel's file, and then starts crawling data from other peers on each channel. At the same time, it outputs each peer's BM and tracker's peer list for each channel in a text file.

We ran the crawler on a PC server with a 512 kbps ADSL home line. The PC configurations were as follows: Window XP, 80 GB hard disk, 2.4 GHz CPU, and 1 GB memory. The data used in the paper were taken on October 26, 2007, and the measurement lasted for about 90 min.

3. Study peers' watching behavior and network sharing

3.1. Summary of the data

The analysis presented was based on our captured trace obtained on October 26, 2007. Three channels were simultaneously crawled for 1.5 h. The generic statistical information of this trace is listed in Table 1. There were a

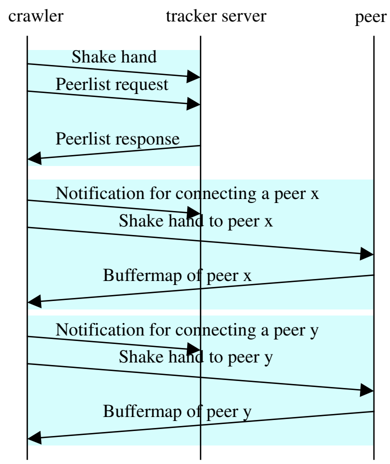

Fig. 2. Protocol sequence for crawling.

Table 1
General information of datasets.

Channel	All	I	II	III
Total records	10865	5319	3086	2460
Maximum chunk ID	139	139	115	136
Total peers	1374	613	432	329
Contributors	1013	455	333	225
Watchers	361	158	99	104

total of 10,865 responses from 1374 different peers. We also named each response as a record. The maximum chunk IDs observed within the 90-min measurement were 139, 115, and 136, and hence, the movie sizes were about 260, 215, and 255 Mbytes for channels 1, 2, and 3, respectively. The numbers of records and the numbers of peers were noticeably different for different channels. However, the average number of responses per peer was close, with the values of 8.6770, 7.1435, and 7.4772 for channels 1, 2, and 3, respectively. This indicates that peers in different channels follow the same protocol and have similar online time distributions.

3.2. Peer's role in a VoD system: contributor and watcher

Peers in a P2P system may play different roles. For example, there are two roles, namely, leecher and seeder, in a BT system. A seeder is a client who has a complete copy of a particular archive, and a leecher is a client who does not have a complete copy of a particular archive. When any new client begins downloading an archive, he/she is a leecher until he/she finishes downloading the entire archive, and subsequently become a seeder. In a P2P live streaming system, all peers are *watchers* and few content servers play the role of *seeders*. Even though BT and P2P live streaming systems are very different systems, peers in these systems play similar roles.

(1) A seeder has the complete archive.
(2) There are many leechers or watchers, but very few seeders in a system.

Based on our measurement, we also observed two roles in a VoD system. However, they were not distinguished based on whether a peer has a complete archive or not. Most peers in VoD system do not have a complete copy of a movie. However, this does not prevent some peers from uploading, while some others download as well as upload in a VoD system. We named a peer who never downloads from other peers (within a given time interval) as a *contributor*, and a peer who does download from others as a *watcher*. A watcher in a VoD system is just like a watcher in a P2P live streaming system. They download chunks from contributors and/or other watchers. Unlike BT and P2P live streaming systems, a contributor in a VoD system may not necessarily have a complete movie. Furthermore, he/she may upload one movie while watching another. A significant difference of a practical VoD system from other P2P volume distribution network, such as BT and live streaming, is that the number of contributors is much more than that of watchers. Our measurement shows that more than two-thirds of the peers are contributors (74%, 77%, and 68% for channels 1, 2, and 3, respectively) within the 90-min measurement interval. This may be the main reason for the P2P-based VoD architecture to outperform the server-based system. In a P2P system, all the online peers who have ever watched a particular channel can be swapped to form a big distributed buffer. Furthermore, the buffer size can be enlarged quickly along with the increasing users who are watching and who have watched that particular movie.

An online peer may advertise his/her BM messages from time to time. We assumed that the bitmap in a BM message is a sequence of 0/1 from the left to right, i.e., the left-most position corresponds to the first chunk. In practice, we can use peers' BM to classify peers. If the number of "1" never increases in a peer's BM during a period of measurement time, then we can categorize this peer as a contributor, or otherwise, as a watcher. Almost every peer whom we examined either advertised an invariant BM or continuously increased new 1s in their BM. Noticeable peers (about 5% peers) even advertised all-zero BMs. For simplicity, we named an all-zero BM as zero BM. Very few peers (<10) changed some bits from 1 to 0 in their advertised BM. However, this happened only at the transient stage, in which a peer advertises a zero BM after a normal BM that he/she had advertised before. We guess the abnormal BM advertisements (zero BM and changes from 1 to 0 in some cases) may be owing to the buggies in the PFSVOD software. An online user may delete his/her file in the middle, but the software only treats the user as a contributor with zero shares. In a more reasonable design, this kind of peer should stop advertising himself/herself, as a contributor with zero shares will only waste the processing capacity of others. We have named the peer who advertises an abnormal BM as *Zpeer*. Thus, we have categorized three types of peers: Contributor, who advertises an invariant and no-zero BM during the entire measurement period; Watcher, who has increased 1s in his/her BM during the measurement; and *Zpeer*, who reports abnormal BM. The dynamic on the number of contributors, watchers, and zpeers is shown in Fig. 3. The fast jump at the beginning around time 0, and down at the end around time 90 min in these subfigures are not accurate, and this trend was observed in most measurements. We did not know if a peer was online before our measurement started and after our measurement ended. Hence, we only measured the time of a peer's first response as his/her online time, and similarly, the time of a peer's last response as his/her offline time. The three subfigures in the right column show the fraction of contributors, watchers, and zpeers. It can be observed that the change in the fractions is much smoother than the change in the absolute numbers. This trend further confirms that the number of contributors is significantly larger than the number of watchers at almost any time point in a VoD system. We may also conclude that a stationary process could approximate the fractions of the numbers, but not the absolute number itself.

3.3. Users' watching behavior in current VoD system: smoother and jumper

A peer's BM records the portion of a movie that he/she has watched. The users' watching behavior can be studied

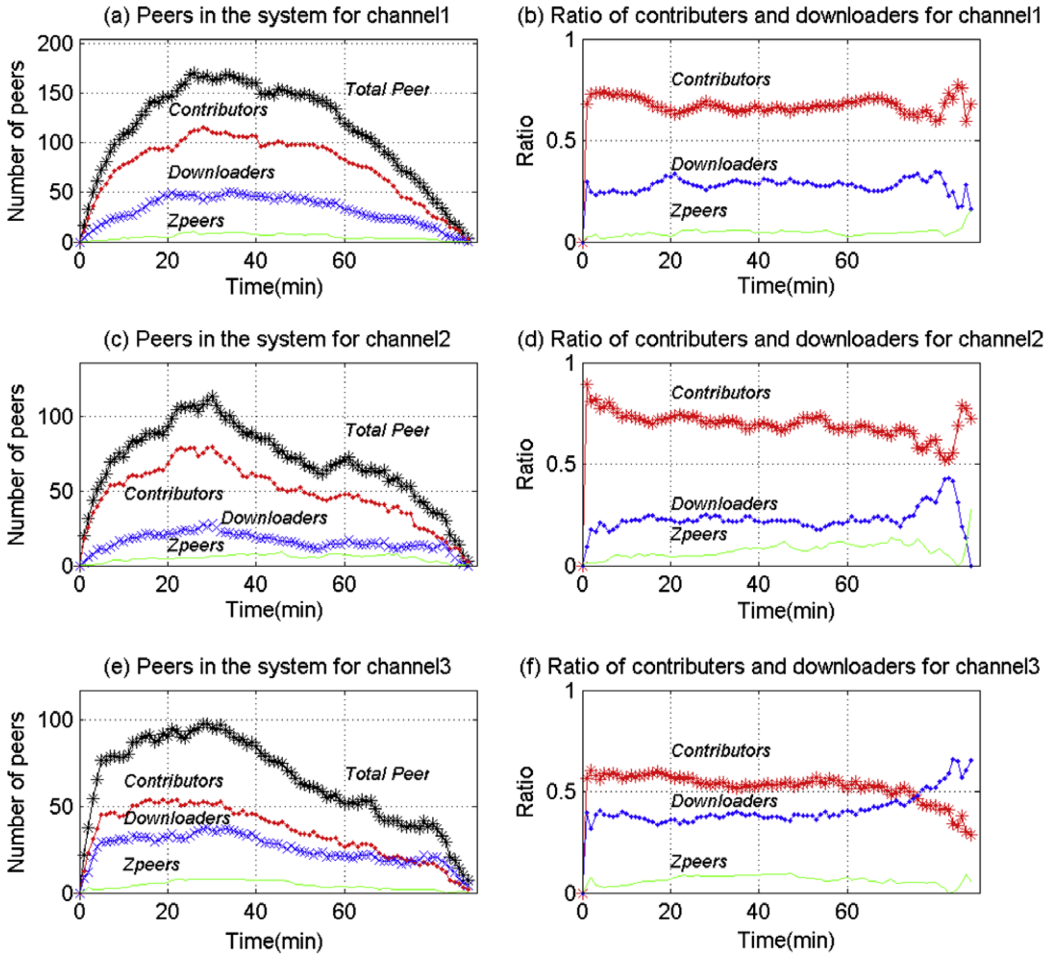

Fig. 3. Number and fraction of peers playing different roles in each channel in our measurement.

through BMs collected during the running of a VoD system. A contributor advertises an invariant BM that reflects his/her watching history. As there exists no time reference in this record, we can only know what this peer has ever watched and not when he/she watched. Hence, only static properties of watching behavior can be obtained by using BM records. A watcher advertises different BM along with the progress of the movie being watched. The dynamic property of watching behavior can be studied if we could collect enough watching peers and their BM. Unfortunately, our preliminary measurement was too short to collect enough watching peers. Hence, we could only study the static properties of contributors' watching behavior in this paper.

In general, movies are ranked based on the number of people who watch it. With the help of BM, we can do more than just counting the number of people. For example, we can tell how long a given movie is watched on an average. We can also tell whether people tend to watch a movie smoothly or jumping from one scene to another. The reason why we studied the users' watching behavior is not only because this problem is a concern for filmmakers and film marketers, but also because watching behaviors affect the network sharing in the VoD environment. The latter is important for VoD system design, and is different from almost all known P2P-based file dissemination systems.

All the P2P-based file dissemination systems involve data-sharing among peers. The efficiency of sharing is related to the topology organization of the network, the neighbor selection, and the scheduling mechanism. However, the efficiency is almost irrelevant to how a user watches those movies. In this paper, we have shown that unlike all the other file systems, the user's watching behaviors do affect the sharing efficiency of a VoD system. Thus, it is possible to improve the sharing efficiency of VoD system through proper (even adaptive) content designs and scheduling.

Only two types of watching modes have been identified from our measured data. People either watch a movie from the start smoothly until they quit in the middle, or watch a movie by jumping from one scene to another. We have named the former as *smooth-watching mode* and the latter as the *jumping watching mode*. People may adopt different modes for different movies. In this paper, we have named a peer in smooth-watching mode as a *smoother*, and the one

Table 2
Number of smoothers and jumpers.

	Contributors				Watchers			
	Smoothers		Jumpers		Smoothers		Jumpers	
	Peers	%	Peers	%	Peers	%	Peers	%
Channel 1	300	70.9	123	29.1	138	87.3	20	12.7
Channel 2	264	86.8	40	13.1	90	90.1	9	9.1
Channel 3	156	73.2	57	26.8	82	78.8	22	21.2

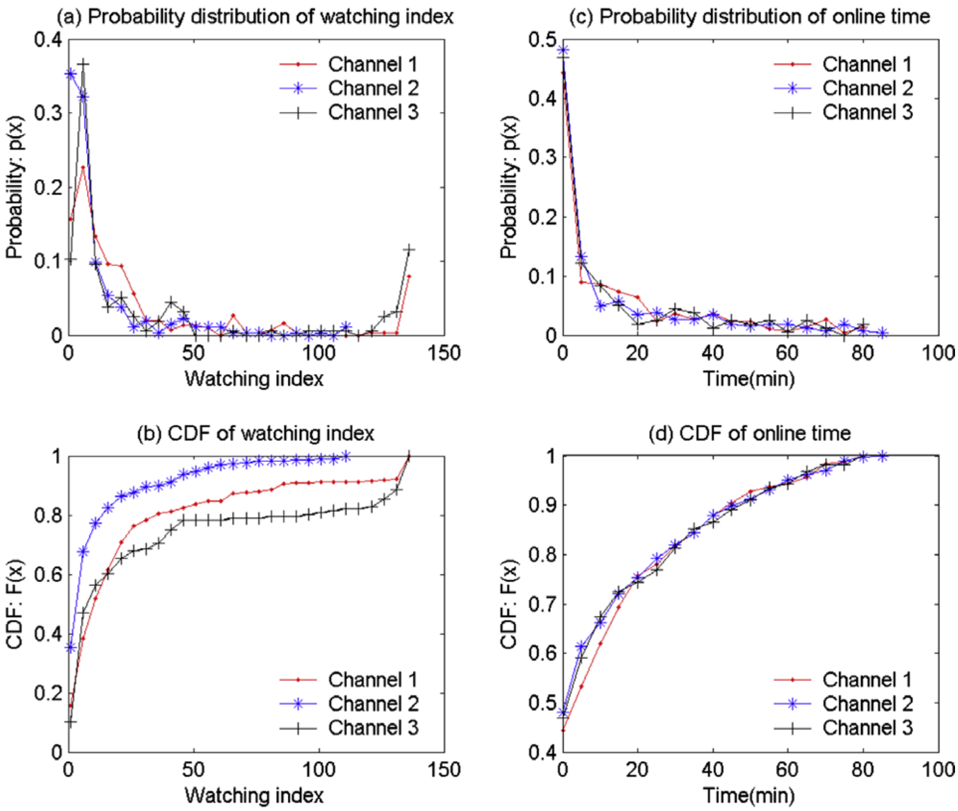

Fig. 4. Distributions of WI and online time for contributors.

in the jumping watching mode as a *jumper*. A smoother has continuous 1s in his/her BM, while a jumper has discrete 1s in his/her BM. The numbers of smoothers and jumpers for contributor and watcher obtained in our trace are listed in Table 2. Based on our measurement, we found that the majority of the peers are smoothers, but the number of jumpers cannot be ignored. This is different from the earlier report [13] that stated that "Most users always perform some random seeking."

For a smoother, the position of the last "1" in its BM explains how many chunks this peer ever watched. We have named this position as the WI of a peer. The WI has also been defined as the *session length* [14]. We used the name WI, because we wanted to emphasize the aspects of time and space in this parameter. Session length only indicates the time duration. As most peers are smoothers, the distribution of WIs may be useful to estimate the attractiveness of a movie to the VoD peers. Generally, a movie with a larger average WI or with longer tail in the distribution of WI is considered to be more attractive. It either means that people watch this movie longer or more people watch the entire movie. In this paper, we used p_{WI} to represent the probability distribution of WI. If we consider that a user has a probability of $p_{\mathrm{WI}}(\theta)$ to watch a movie until chunk θ, then it can be calculated as the fraction of peers such that the last "1" in their BM is in the position θ. Fig. 4a shows $p_{\mathrm{WI}}(\theta)$, the probability distribution of WI calculated from our measurement, while Fig. 4b shows $F_{\mathrm{WI}}(\theta) = \Sigma_{k \leqslant \theta} p_{\mathrm{WI}}(k)$, the cumulative distribution function (CDF) of WI. Based on these distributions, channel 3 was found to be the most attractive program and channel 2 was the least attractive program. Unlike the WI that indicates how many chunks (equivalently how long) of a movie is watched by a peer, the online time of a peer is the time duration for which a peer stays in a channel. The probability distribution of online time depicted in Fig. 4c is the fraction of peers who stay in the system for a given time interval. While the distributions of WI are significantly different, the distributions of online time are very similar among different channels. This indicates that a peer's WI is strongly related to the program played in a channel; while a contributor's online time is independent of what his/her current contribution.

Fig. 5 shows the BM occupancies of contributors. The subfigures in left column (Fig. 5a, c and e) are the BM for jumpers. The x-axis is the chunk ID or bit positions in the BM. The y-axis is the jumpers ranked by their WIs. Each horizontal line in these subfigures corresponds to one jumper. The line on the top represents the jumper with the highest WI. The solid red lines in these subfigures show the WIs of the jumpers. A black dot in (x, y) represents a jump for peer y at the chunk x. For any given peer y, his/her BM has 0s in those x-positions that are either to the right of the intersection of the red curve and horizontal line y or have black dots at the horizontal line y. The subfigures in the right column (Fig. 5b, d and f) are the cumulated distribution of WI for smoothers and jumpers. The x-axis of these subfigures is the same as that of the left subfigures. The y-axis is the fraction of the peers. The blue solid line and red dashed line in those subfigures are the WI of smoother and jumper, respectively. The thick black line is the number of 1s in the jumpers' BM or the number of chunks that a jumper has watched. To our knowledge, the difference in terms of WI distributions between the smoothers and jumpers has not been reported earlier. Hence, we have made more efforts to discuss how this difference may influence sharing in the network. As a peer advertises his/her BM to indicate what he/she is capable of and willing to share, those subfigures can also be interpreted as the sharing map of peers in a VoD system. Based on this interpretation, we can draw the following conclusions about the watching behavior and file-sharing in a VoD system:

(1) Even though most people today adopt smooth-watching mode, it may not be a good mode for file-sharing. As a lot of people only watch a movie for few chunks, this mode may result in overprovision around those starting chunks and under provision for other chunks, especially for those chunks near the end.
(2) Jumping watching mode in a VoD system promotes file-sharing. In those right subfigures of Fig. 5, one can easily find that the thick black line is significantly below the blue solid line. This indicates that a jumper generally contributes more chunks than a smoother. Furthermore, the red dash line lies below both the blue solid line and the thick black line,

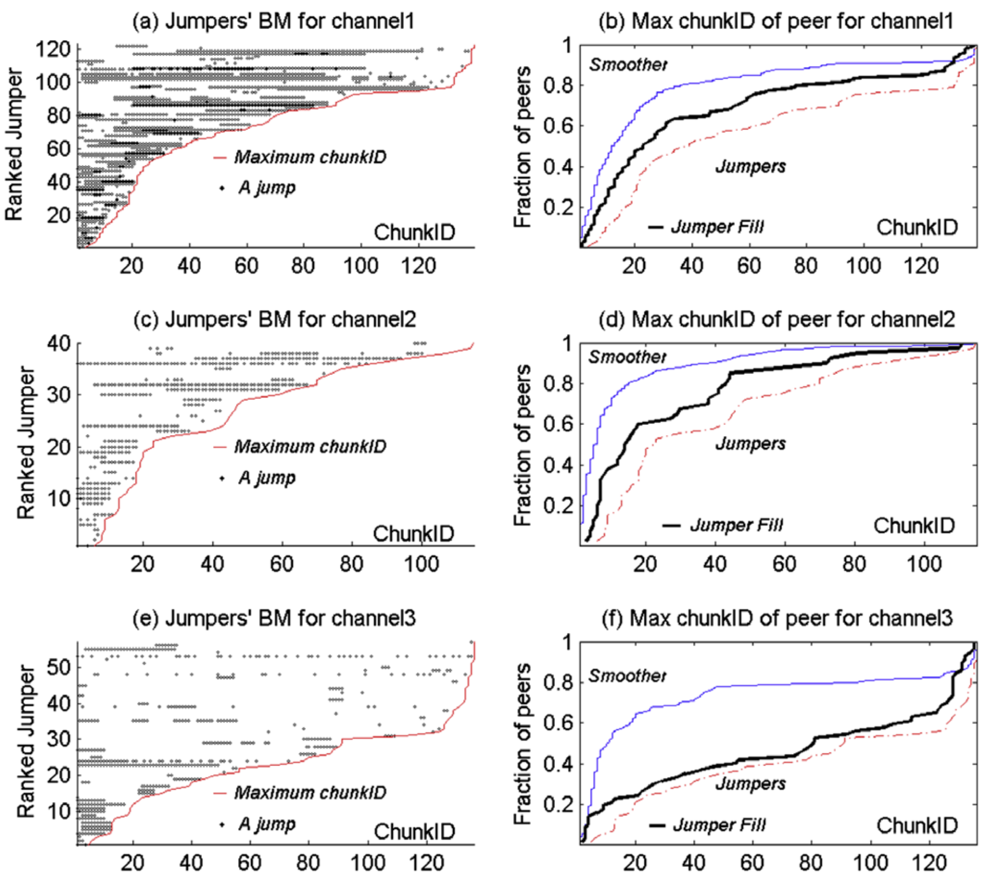

Fig. 5. BM occupancies of contributors.

indicating that a jumper also contributes chunks with large IDs (chunks at the end of a movie) that a smoother may not be able to contribute.

(3) In fact, even if jumpers contribute less chunks, the existence of jumpers is still valuable, as the unbalanced provision status resulted by smoothers can be compensated by the jumpers.

In summary, we believe that a VoD system should facilitate jumping watching mode at least in the current stage. To promote user jump, we need a movie that is suitable to watch by jumping and a network protocol that supports user jump. In addition, smaller chunk size and fast re-setup may be important features to this network protocol.

3.4. Network sharing

In a P2P-based file system, the number of copies is an important indication to the availability of sharing. A peer can easily find and quickly download pieces with larger number of copies. Availability $N(\theta,t)$ is the number of copies of chunk θ in the network at a given time t. Equivalently, the availability of a chunk at a time is the number of peers who are online and possess this chunk at this time. Fig. 6 shows the chunk availability provided by contributors in our measurement. Subfigures at the top are the two-dimensional (2D) representations. Each curve in a subfigure stands for one chunk. The subfigures at the bottom are the three-dimensional (3D) representations. From these figures, we can easily find that chunks with larger IDs have less availability. Furthermore, all the curves are not stationary, and studying the availability for each curve will be a very tedious work. Fortunately, if we normalize the availability $N(\theta,t)$ by the number of online peers $N(t)$, or the number of total copies $C(t)=\Sigma_\theta N(\theta,t)$ at time t, then both the resulting functions, $\eta(\theta,t)=N(\theta,t)/N(t)\approx\eta(\theta)$ and $\xi(\theta,t)=N(\theta,t)/C(t)\approx\xi(\theta)$, can be observed to be almost independent of time t. We have named the normalized availability as the *sharing profile* (SP), $\eta(\theta)$, and *sharing distribution* (SD), $\xi(\theta)$. The latter is a probability distribution as $\Sigma_\theta\xi(\theta)=1$, while the former is not. The sharing profiles $\eta(:,t)$ and sharing distributions $\xi(:,t)$ are shown in Fig. 7. There are six subfigures shown in two rows. The top three subfigures show the sharing profile and the bottom three subfigures indicate the sharing distribution. The subfigures in each column correspond to one channel. There are 86 curves in light color in each subfigure, which correspond to the sharing profile (on the top) or distribution (in the bottom), calculated at time 1, 2, ..., 86 min from the start time of the measurement. All the light colored curves in one subfigure are very similar. This indicates that the sharing profile and sharing distribution is well defined in a practical P2P VoD system. The availability of chunks can be approximately expressed by either $N(\theta,t)=N(t)\eta(\theta)$ or $N(\theta,t)=C(t)\xi(\theta)$. The thick black curve in each subfigure of Fig. 7 is calculated using the distribution of WI by Theorem 1, which will be discussed in the subsequent subsection. It can be observed that the thick

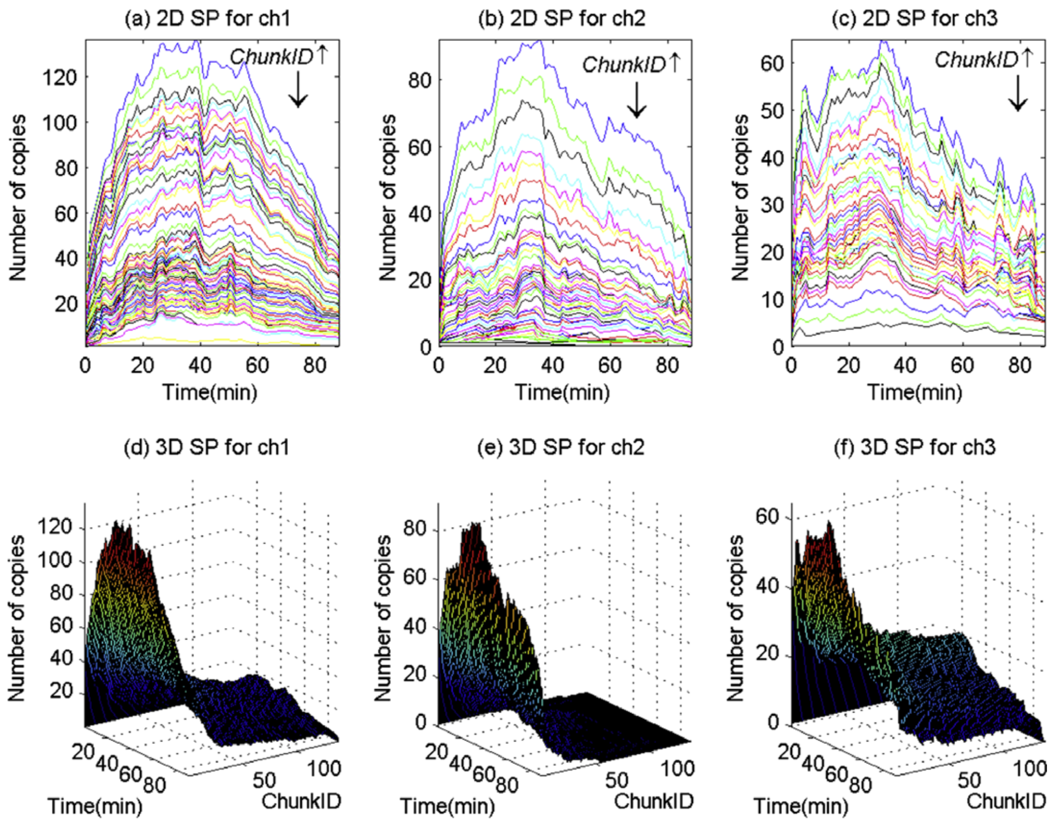

Fig. 6. Availability of chunks at different time.

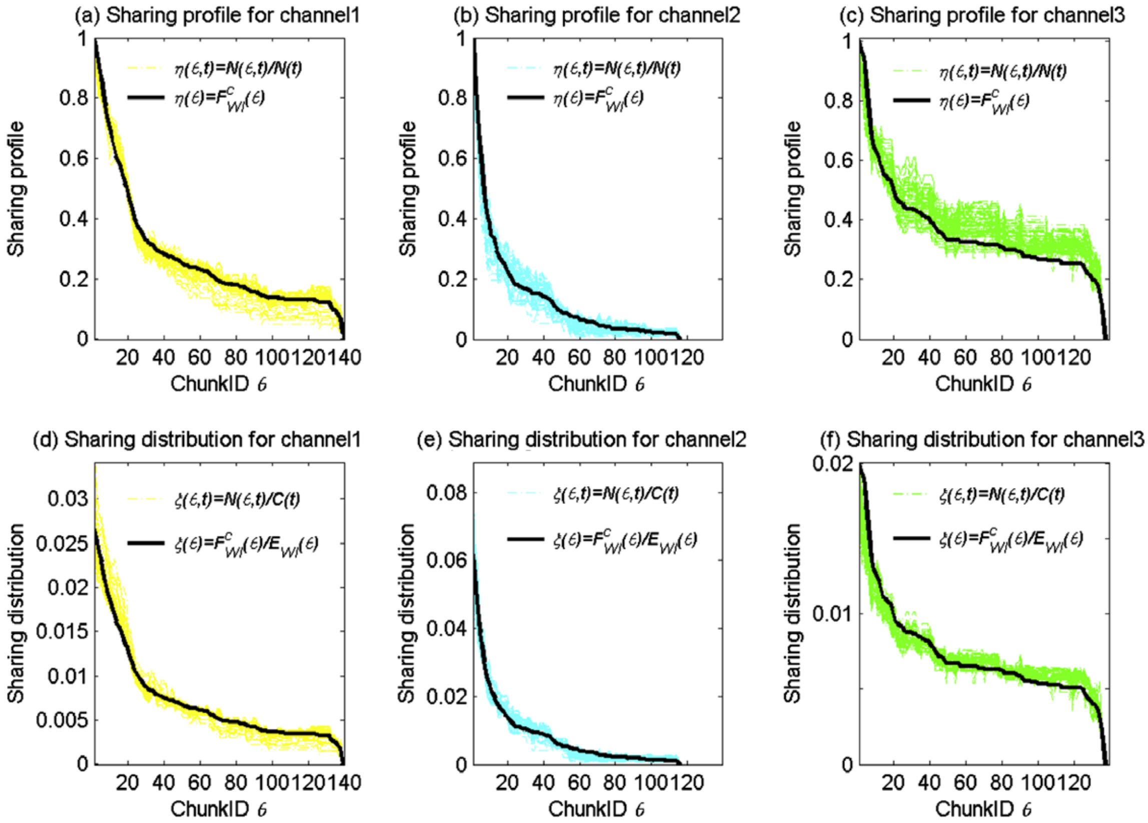

Fig. 7. Sharing profiles and sharing distributions.

black curve matches well with the light colored curves. In the next section, we will introduce a simple analytical model to show the firm relationship among the distribution of WI, sharing profile, and sharing distribution.

3.5. Watching index and network sharing

In the previous section, we showed that the availability $N(\theta,t)$, the number of online peers $N(t)$, and the number of total copies $C(t)$ fluctuate with time t, while the sharing profile $\eta(\theta,t)$ and sharing distribution $\xi(\theta,t)$ are almost time-invariant. Hence, we can assume a time-invariant sharing profile $\eta(\theta)$ and sharing distribution $\xi(\theta)$. In this section, we will prove that the sharing profile $\eta(\theta)$ and sharing distribution $\xi(\theta)$ can be analytically deduced from the distribution of WI, $p_{\mathrm{WI}}(\theta)$. This further verifies the time-invariant property of sharing profile and sharing distribution.

Lemma 1. *Let $N(t)$ be the set of online smoothers at time t. Every peer in $N(t)$ can be assumed to have a WI distribution, $p_{\mathrm{WI}}(\theta,t)$. Thus,*

(1) *The sharing profile $\eta(\theta,t)$ at time t can be calculated as follows:*

$$\eta(\theta,t) = F^c_{\mathrm{WI}}(\theta,t) = 1 - \sum_{k=1}^{\theta-1} p_{\mathrm{WI}}(k,t). \tag{1}$$

(2) *The number of total copies $C(t)$ at time t can be calculated as follows:*

$$C(t) = N(t)E_{\mathrm{WI}}(\theta,t), \tag{2}$$

where $E_{\mathrm{WI}}(\theta,t) = \Sigma_k p_{\mathrm{WI}}(k,t)$ is the expectation of WI at time t.

Proof. For ease of presentation, we have omitted time t in the proof. All the numbers involved are supposed to be the values at time t. For example, we have used N and C to represent $N(t)$ and $C(t)$, respectively, without causing confusion. Let N be the set of online peers with no-zero BM, and $M_\theta \subseteq N$ be the set of smoothers with a WI, θ. As a smoother watches a movie continuously, if a peer has a WI of θ, he/she must have all chunks from chunk 1 to chunk θ. Let N_θ be the set of online peers who have chunk θ, then $N_\theta = \cup_{k\geqslant\theta} M_k$. As M_θ are disjoint for different θ, $|N_\theta| = \Sigma_{k\geqslant\theta}|M_k| = N - \Sigma_{k<\theta}|M_k|$. By the definition of sharing profile, we have

$$\begin{aligned}\eta(\theta,t) &= |N_\theta|/|N| = 1 - \sum_{k=1}^{\theta-1}|M_k|/|N| \\ &= 1 - \sum_{k=1}^{\theta-1} p_{\mathrm{WI}}(k,t).\end{aligned} \tag{3}$$

Thus, we have proved Eq. (1). For Eq. (2), the number of total copies is equal to the sum of N_θ for all θ. Thus, we have

$$\begin{aligned}C &= \sum_\theta |N_\theta| = N\sum_\theta |N_\theta|/|N| = N\sum_\theta\left(\sum_{k\geqslant\theta} p_{\mathrm{WI}}(k,t)\right) \\ &= NE_{\mathrm{WI}}(\theta,t). \quad \square\end{aligned} \tag{4}$$

Lemma 2. *Let N be a set of smoothers and $M \subseteq N$ be a randomly selected subset of N. Then, the set N and subset M may have the same WI distribution.*

Proof. It is a restatement of the random sampling theorem stating that a distribution on a sample set and its mother set is the same if the sample set is randomly drawn from the mother set. □

Based on the above-mentioned lemmas, if the online/offline processes of a peer is independent of what he/she stores, then the observed sharing profile will be approximately time invariant, as WI distribution is time invariant. Fig. 4 provides certain evidence on the independency between peers' WIs and online processes. In the remainder of this paper, we will assume a time-invariant sharing profile and sharing distribution to study the relations among the distribution of WI, sharing profile, and sharing distribution. Under this assumption, we can summarize the above-mentioned lemmas into the following theorem.

Theorem 1. *Let $p_{\mathrm{WI}}(\theta)$, $\eta(\theta)$, and $\xi(\theta)$ be the distribution of WI, sharing profile, and sharing distribution of a given channel, respectively. Thus, we have following equations:*

$$\eta(\theta) = F^c_{\mathrm{WI}}(\theta) = 1 - \sum_{k=1}^{\theta-1} p_{\mathrm{WI}}(k), \tag{5}$$

$$\xi(\theta) = \frac{F^c_{\mathrm{WI}}(\theta)}{E_{\mathrm{WI}}(\theta)} = \frac{1 - \sum_{k=0}^{\theta-1} p_{\mathrm{WI}}(k)}{\sum_{k=1}^{\infty} k p_{\mathrm{WI}}(k)}, \tag{6}$$

$$E_\xi(\theta) = \sum_\theta \theta\xi(\theta) = \frac{1}{2}(1 + D_{\mathrm{WI}}(\theta)/E_{\mathrm{WI}}(\theta)). \tag{7}$$

Proof. Eq. (5) is simply the combination of Lemmas 1 and 2. For Eq. (6), using Eq. (2) in Lemma 1, we get

$$\xi(\theta) = \eta(\theta)N(t)/C(t) = \frac{F^c_{\mathrm{WI}}(\theta)}{E_{\mathrm{WI}}(\theta)} = \frac{1 - \sum_{k=0}^{\theta-1} p_{\mathrm{WI}}(k)}{\sum_{k=1}^{\infty} k p_{\mathrm{WI}}(k)}. \tag{8}$$

Finally, for Eq. (7), we have

$$\begin{aligned} E_\xi(\theta) &= \textstyle\sum_\theta \theta\xi(\theta) \\ &= \frac{(p_{\mathrm{WI}}(1) + p_{\mathrm{WI}}(2) + \cdots) + 2(p_{\mathrm{WI}}(2) + p_{\mathrm{WI}}(3) + \cdots) + \cdots}{E_{\mathrm{WI}}(\theta)} \\ &= \frac{\sum_\theta \theta(\theta+1) p_{\mathrm{WI}}(\theta)}{2E_{\mathrm{WI}}(\theta)} = \frac{\sum_\theta \theta^2 p_{\mathrm{WI}}(\theta) + \sum_\theta \theta p_{\mathrm{WI}}(\theta)}{2E_{\mathrm{WI}}(\theta)} \\ &= \frac{1}{2}(1 + D_{\mathrm{WI}}(\theta)/E_{\mathrm{WI}}(\theta)). \quad \square \end{aligned} \tag{9}$$

Theorem 1 can be validated by Fig. 7. In each subfigure of Fig. 7, the thick black curve shows the calculated result from Theorem 1. This thick black curve matches the light colored curves quite well in each subfigure.

The last equation in Theorem 1 indicates that the average number of chunk copies is related to the second moment of the WI. This indicates that the diversity in users' watching behaviors may promote network sharing in a VoD system, and this provides the following twofold insights: first, the protocol of VoD should facilitate any kinds of watching habits. Those habits may contain starting watching from the middle, watching a movie by jumping, and even watching a movie backward from the end to the beginning. Second, a movie should be designed to lure its viewers to present different behaviors. For example, guiding different viewers go to different sections by properly designed preview. In short, a good VoD system should comprise well-designed network protocols as well as shared contents to accommodate any kind of audience.

3.6. Sharing profile and sharing distribution for jumpers

Strictly, the earlier discussions are only applicable to smoothers, as their BMs are consecutive. In this subsection, we will study the sharing properties of jumpers. It is hard to exactly describe the peers' seeking pattern [14]. The skipping probability can be defined from different points of view. In a global view, this probability $\lambda(\theta)$ can be defined as the fraction of jumpers that skip chunk θ among all the jumpers who have a WI $> \theta$. Fig. 8 shows the skipping probability $\lambda(\theta)$ for each chunk θ. If the probability is known, then we could find the sharing characteristics of the jumpers from the following theorem:

Theorem 2. *Let $p_{\mathrm{WI}}(\theta)$, $\eta(\theta)$, $\xi(\theta)$, and $\lambda(\theta)$ be the distribution of WI, sharing profile, sharing distribution, and skipping probability of the jumpers, respectively, in a given channel. Thus, we can derive the following sharing equations:*

$$\eta(\theta) = (1 - \lambda(\theta))F^c_{\mathrm{WI}}(\theta), \tag{10}$$

$$\xi(\theta) = \frac{(1 - \lambda(\theta))F^c_{\mathrm{WI}}(\theta)}{\sum_\theta (1 - \lambda(\theta))F_{\mathrm{WI}}(\theta)}. \tag{11}$$

Proof. Similar to the proof of Theorem 1, let N be the set of online peers with non-zero BM, $M_\theta \subseteq N$ be the set of jumpers whose WIs are θ, $N_\theta \subseteq \cup_{k \geqslant \theta} M_k$ be the set of jumpers whose WIs are $\geqslant \theta$, and $L_\theta \subseteq N_\theta$ be the set of jumpers who have the chunk θ. By the definition of sharing profile, we have

$$\begin{aligned} \eta(\theta) &= |L_\theta|/|N| = (|L_\theta|/N_\theta)(|N_\theta|/|N|) \\ &= (1 - \lambda(\theta))\left(1 - \sum_{k=1}^{\theta-1} |M_\theta|/|N|\right) \\ &= (1 - \lambda(\theta))\left(1 - \sum_{k=1}^{\theta-1} p_{\mathrm{WI}}(k)\right) \\ &= (1 - \lambda(\theta))F^c_{\mathrm{WI}}(\theta) \end{aligned} \tag{12}$$

and

$$\begin{aligned} C(\theta) &= \sum_\theta |L_\theta| = N\sum_\theta (|L_\theta|/|N_\theta|)(|N_\theta|/|N|) \\ &= N\sum_\theta (1 - \lambda(\theta))\left(\sum_{k \geqslant \theta} p_{\mathrm{WI}}(k)\right) \\ &= N\sum_\theta (1 - \lambda(\theta))F_{\mathrm{WI}}(\theta). \quad \square \end{aligned} \tag{13}$$

With regard to a peer's behavior, the simplest model is to imagine a jumper to skip any chunk (with ID less than its WI) by a constant probability, λ. In this simple skipping model, the skipping probability, $\lambda(\theta)$ would be a constant, $\lambda(\theta) = \lambda$. The thick dashed line in Fig. 8 shows this probability. Noticeable differences between the marked line and thick dashed line can be observed for each channel, indicating that our simple model slightly differs from the

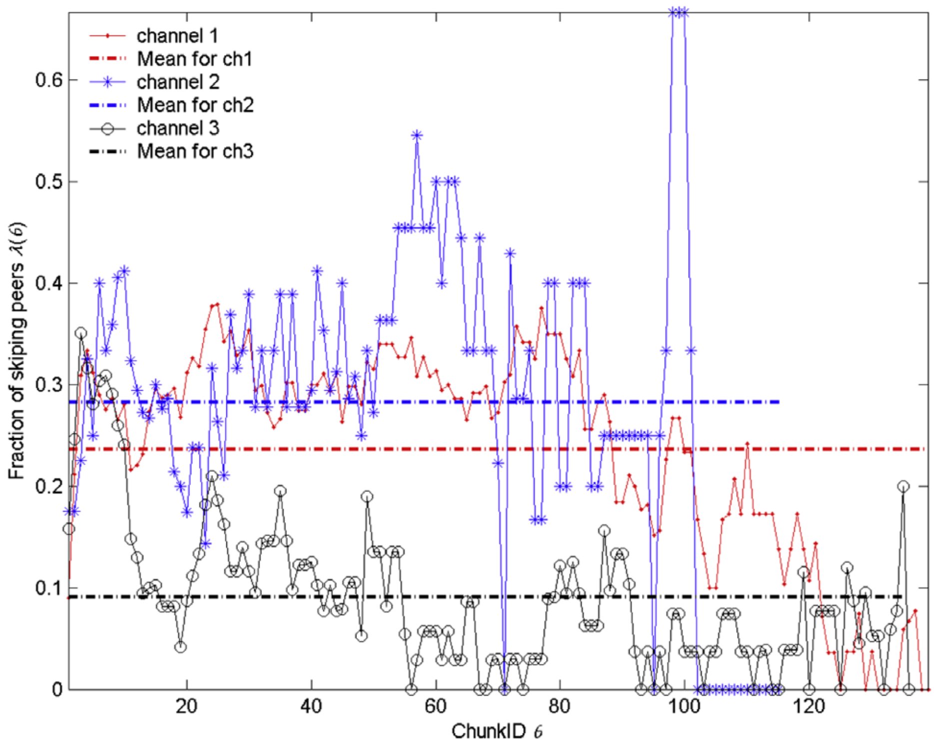

Fig. 8. Skipping probability of jumpers.

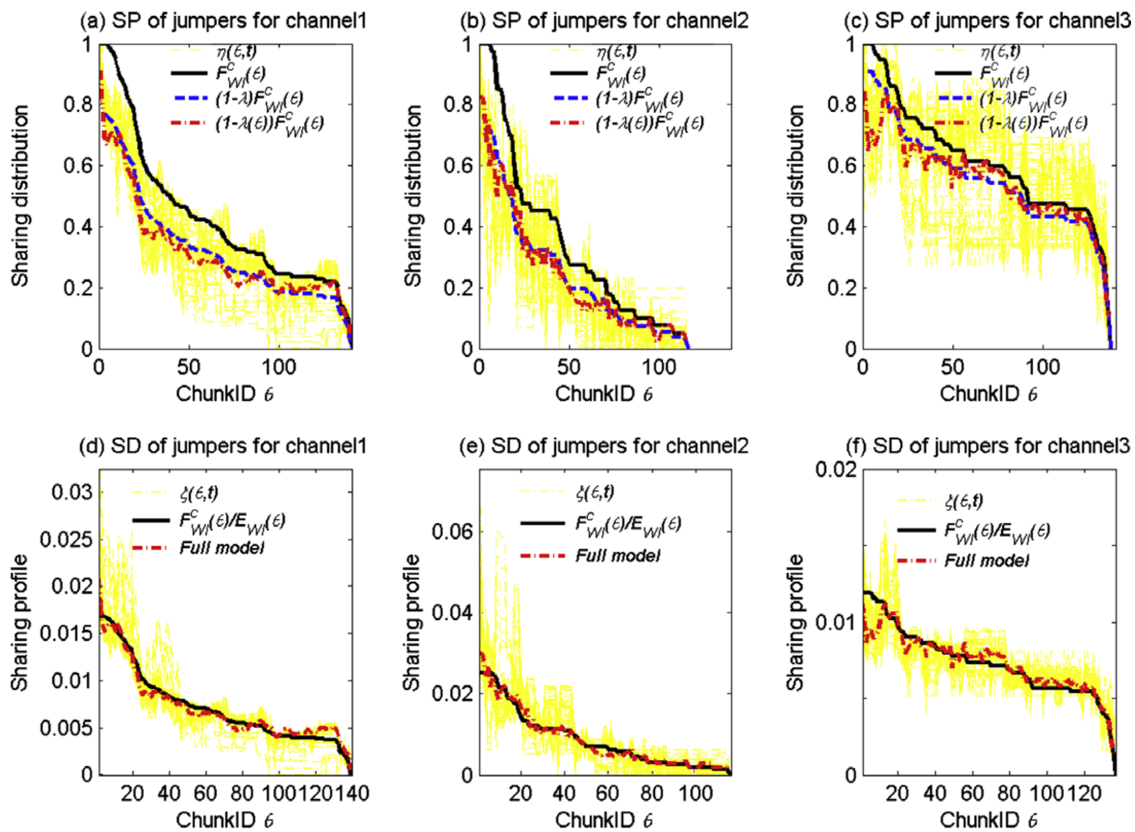

Fig. 9. Sharing profiles and distributions for jumpers.

real system. However, this simple model is still attractive owing to its simplicity. We have used the mean of $\lambda(\theta)$ as the value of λ in our simple model. The values of λ for channel 1, 2, and 3 are 0.24, 0.28, and 0.09, respectively. By substituting $\lambda(\theta) = \lambda$ in the equations in Theorem 2, we can directly obtain the following corollary.

Corollary. *Let λ be the skipping probability in our simple skipping model. Thus, the sharing profile and sharing distribution for jumpers can be obtained as follows:*

$$\eta(\theta) = (1-\lambda)F^c_{\mathrm{WI}}(\theta), \tag{14}$$

$$\xi(\theta) = F^c_{\mathrm{WI}}(\theta)/E_{\mathrm{WI}}(\theta). \tag{15}$$

It must be noted that the sharing distribution for the simple skipping model is the same as that without skipping. Fig. 9 shows the sharing profile and sharing distributions for jumpers. The subfigures in Fig. 9 in every column are for the same channel. The subfigures at the top indicate the sharing profile and those at the bottom show the sharing distribution. Similar to Fig. 7, the yellow curves are the measured sharing profiles (top) and sharing distributions (bottom). The thick black solid line in each subfigure shows the sharing profiles (top) and sharing distributions (bottom) when skipping is not considered. In other words, the thick black solid line is calculated by Theorem 1. Based on the above-mentioned corollary, this line in those subfigures at the bottom also shows the sharing distribution of simple skipping model. The thick blue dashed line in the top subfigures shows the sharing profile for simple skipping model. The thick red dotted line in those subfigures shows the sharing profile (top) or sharing distribution (bottom) from the exact skipping probability $\lambda(\theta)$ in Fig. 8. It can be noted that the curves of the sharing profile or sharing distribution for simple model and exact skipping probability are similar. The curve for exact skipping probability has more fluctuations, but that for simple model is smoother. The exact skipping probability is more suitable to study the cases when one wants to consider seeking patterns. If one wishes to ignore the seeking pattern, then simple skipping model is a good candidate to approximate the network sharing.

4. Conclusion

In this paper, P2P-based VoD system has been briefly introduced, and our reverse engineering on the protocol and message format of PFSVOD and PPStreamVOD systems has been outlined. The peers' watching behavior has been studied through the measured BM by our newly proposed method. We observed that there are more upload-only peers than download peers, and smooth-watching peers are more than jumping peers in the currently deployed P2P VoD systems. This finding is noticeably different from the existing P2P-based file dissemination systems and the observations made in previous work on server based VoD systems. The relations between peers' watching behavior and network sharing have been revealed in this paper. Randomly-seeking peers have been observed to provide more regular chunks as well as rare chunks for sharing, than smooth-watching peers. A simple mathematical model has been established to analytically show the relation between the distribution of WI and sharing profile, which was also validated by our measurement data in this paper.

Beyond helping to understand the current P2P VoD system, our work also suggests that better user experience can be expected by improving the VoD streaming protocols as well as the content designs, as the network sharing in this system is strongly related to the watching behavior of the users. A good streaming protocol should accommodate a variety of users' watching habits, including random seeking. Properly designed preview and directory of a movie may promote different audience to adopt different watching styles. Furthermore, balance in chunks' availability can be improved through diversities in peers' watching behaviors.

Acknowledgment

We thank Prof. Baoxian Zhang for the zealous discussions on this topic as well as for the helpful revisions and suggestions on the presentation of this paper.

References

[1] X. Zhang, J. Liu, B. Li, T.-S.P. Yum, Coolstreaming/Donet: a data-driven overlay network for peer-to-peer live media streaming, in: Proceedings of INFOCOM 2005, Miami, FL, 2005.
[2] X. Hei, C. Liang, J. Liang, Y. Liu, K.W. Ross, A measurement study of a large-scale P2P IPTV system, IEEE Transactions on Multimedia 9 (8) (2007) 1672–1687 (Also Polytechnic U., Tech. Rep., 2006 and IMC 06).
[3] X. Hei, C. Liang, J. Liang, Y. Liu, K.W. Ross, Insights into PPLive: a measurement study of a large-scale P2P IPTV system, in: Proceedings of IPTV Workshop in Conjunction with WWW2006, Scotland, United Kingdom, 2006.
[4] S. Ali, A. Mathur, H. Zhang, Measurement of commercial peer-to-peer live video streaming, First Workshop on Recent Advances in Peer-to-Peer Streaming, 2006.
[5] L. Vu, I. Gupta, J. Liang, K. Nahrstedt, Mapping the PPLive network: studying the impacts of media streaming on P2P overlays, UIUC Tech. Rep., 2006.
[6] Y. James Hall, P. Piemonte, M. Weyant, Joost: a measurement study. <http://www.patrickpiemonte.com/15744-Joost.pdf>.
[7] B. Cheng, H. Jin, X.F. Liao, RINDY: a ring based overlay network for peer-to-peer on-demand streaming, in: Proceedings of Ubiquitous Intelligence and Computing, Wuhan, 2006.
[8] T. Do, K.A. Hua, and M. Tantaoui, "P2VoD: providing fault tolerant videoon-demand streaming in peer-to-peer environment", Proceedings of IEEE ICC'04, 2004.
[9] Y. Guo, K. Suh, J. Kurose, D. Towsley, A peer-to-peer on-demand streaming service and its performance evaluation, in: Proceedings of ICME'03, 2003.
[10] C.S. Liao, W.H. Sun, C.T. King, H.C. Hsiao, OBN: peering for finding suppliers in P2P on-demand streaming systems, in: Proceedings of the Twelfth International Conference on Parallel and Distributed Systems (ICPADS'06), 2006.
[11] C. Huang, J. Li, K.W. Ross, Can internet video-on-demand be profitable? in: Proceedings of ACM Sigcomm, 2007.
[12] B. Cheng, X. Liu, Zhang, H. Jin, A measurement study of a peer-to-peer video-on-demand system, in: Proceedings of IPTPS07.
[13] C.X. Zheng, G.B. Shen, S.P. Li, Distributed pre-fetching scheme for random seek support in peer-to-peer streaming applications, in: Proceedings of the ACM Workshop on Advances in Peer-to-Peer Multimedia Streaming, Hilton, Singapore, 2005.
[14] H.L. Yu, D.D. Zheng, B.Y. Zhao, W.M. Zheng, Understanding user behavior in large-scale video-on-demand systems, in: Proceedings of Eurosys'06, Belgium, 2006.
[15] B. Cohen, Incentives build robustness in BitTorrent, in: IPTPS, 2003.
[16] D. Qiu, R. Srikant, Modeling and performance analysis of BitTorrent-like peer-peer networks, in: Proceedings of ACM SIGCOMM 2004, 2004.
[17] S. Tewari, L. Kleinrock, Analytical model for BitTorrent-based live video streaming, in: Proceedings of Consumer Communications and Networking Conference, 2007.
[18] "PPLive", <http://www.pplive.com/>.
[19] "Joost", <http://www.joost.com/>.

[20] "PFSVOD", <http://www.pplive.com/subject/20070808pfsVoD/>.
[21] "PPStream", <http://www.ppstream.com/>.
[22] Y.Huang, T.Z.J. Fu, D. Chiu, J.C.S. Lui, C. Huang, Challenges, design and analysis of a large-scale P2P-VoD system, in: Proceedings of ACM Sigcomm, 2008.

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