Peer-to-Peer Netw. Appl.
DOI 10.1007/s12083-014-0268-0

Exploring the policy selection of the P2P VoD system: A simulation-based research

Ke Xu · Xin Liu · Zhen Ma · Yifeng Zhong · Wenlong Chen

Received: 27 June 2013 / Accepted: 12 March 2014

Abstract The P2P-based video-on-demand (P2P VoD) service has achieved tremendous success among Internet users, and attracted many researchers' interest. Piece selection policy, peer selection policy and replica management policy are three important policies in P2P VoD systems. Although there has been some research work on the policy selection of the P2P VoD system, it still remains unknown that which policy composition is better for the system. Different from the existing research, we study the existing P2P VoD policies by using a simulation framework to understand the features as well as the performance of different policy compositions. The simulation results indicate that when the bandwidth and storage resources are limited in the P2P VoD system, the composition of the sequential piece selection policy, the cascading peer selection policy and the proportional replica management policy has the best performance among all the different policy compositions. However, when the bandwidth and storage resources are sufficient in the system, there will be little difference between different policies. To further understand such a system, we also explore the impact of resources on policies selection. Our simulation provides evidence that theoretically the P2P VoD system can work well without extra replica space as long as the bandwidth of the peers is large enough, but the extra storage space can help improve the performance of the system in practical scenarios where the peers' bandwidth is limited.

Keywords P2P VoD streaming · Piece selection policy · Peer selection policy · Replica management policy

K. Xu (✉) · Y. Zhong
Department of Computer Science and Technology, Tsinghua University, Beijing, China
e-mail: xuke1974@gmail.com

X. Liu
Department of Computer Science and Technology, Tsinghua University, Beijing, China

X. Liu
China Mobile Corp, Beijing, China

Z. Ma
Google Inc, Mountain View, CA, USA

W. Chen
College of Information Engineering, Capital Normal University, Beijing, China

1 Introduction

The peer-to-peer (P2P) technology has witnessed a great development in the past decade, and is widely used in the area of file sharing, audio and video streaming. It has been several years since P2P video-on-demand (VoD) service started to develop, and there have been many P2P VoD systems designed for Internet users, such as GridCast[1] [1], PPLive[2] [2], Joost[3] [3] and UUSee[4] [4]. Apart from system design and measurement work, there still exist some model analysis working on system strategies, such as [5–9].

Based on the previous P2P VoD system design works[1, 2, 4], the piece selection policy, the peer selection policy and the replica management policy are the core strategies of the P2P VoD system. Although these policies have been studied in a great amount of research works before, some fundamental questions have not been answered yet. In this paper, we focus on the following questions: (1) *Which policy is more important among the three core strategies of the P2P VoD system?* (2) *Which policy composition will be the best choice for the*

[1] http://gridcast.web.cern.ch/Gridcast/
[2] http://www.pptv.com/
[3] http://www.joost.com/
[4] http://download.uusee.com/

Published online: 29 March 2014

P2P VoD system? (3) *How will the bandwidth and storage resources influence policies choosing?* To answer these questions, like the design space analysis on the incentive mechanisms in [10], we build a simulation framework to simulate the P2P VoD system which uses different policies. In the previous version of this paper [11], we use the simulation framework to research the first two questions. In this paper, we conduct research on the robustness and scalability of the P2P VoD system's policies. We also discuss the importance of different resources in the P2P VoD system.

In our simulation, we first compare the performance of different policy selections in different scenarios, and then the performance of different policy compositions. Our simulation results show that the performance of different piece and peer selection policies varies a lot when the resources in the P2P VoD system are limited. Hence, we should give more emphasis to the optimization of the piece and peer selection policies. The sequential piece selection policy, the cascading peer selection policy and the proportional replica management policy are the best[5] choices for the P2P VoD system when the resources are limited. The composition of the previously selected three policies also has the best performance among all policy compositions. However, the simulation results also indicate that there is just a little difference among different policy compositions when the resources are sufficient in the P2P VoD system. Therefore, theoretically strategies do not need to be optimized if the bandwidth and storage resources are sufficient in the P2P VoD system.

In addition, the importance of the resources in the P2P VoD system is evaluated by using simulation. The system performance will increase if the bandwidth or storage space of peers grows. However, it will not have much effect if we just increase bandwidth when the storage space is limited. When the bandwidth is sufficient, there will be little effect even though we increase the storage space of peers. Therefore, theoretically the P2P VoD system can work well without extra replica space as long as the bandwidth of peers is large enough. However, the extra storage space can help improve the performance of the system in practical scenarios where the peers' bandwidth is limited. Our discussion result shows that the storage space has limited effect on improving the peers' upload bandwidth usage. Hence, we think the system provider should give more importance to increasing bandwidth for its provision of better streaming service.

The rest of this paper is organized as follows: we first summarize the related work in Section 2, and then we introduce the possible choices of these three policies in Section 3. In Section 4, the framework of our simulation is presented, and in Section 5 the result analysis of the simulation is shown. The paper is concluded in Section 6.

[5] It should be noted that these policy choices are the best among those choices we research but not all possible ones.

2 Related work

The peer-to-peer video-on-demand system has witnessed a significant development in the past a few years. Many researchers and technicians have also paid much attention to the P2P VoD system, and their research mainly concentrate on P2P VoD system designs, measurements and model analysis.

CoolStreaming [12], the first practical P2P live media streaming system released in 2004, presented a data-driven overlay network solution to the streaming system and indicated the great potential of P2P technology in streaming service. After CoolStreaming, plenty of new P2P live streaming and video-on-demand systems emerged, such as PPLive [2], GridCast [1], PPStream [13], UUSee [4] and Joost[3]. PPLive discussed the challenges and the architectural design issues of a large-scale P2P-VoD system based on the experiences of the real system deployed by PPLive. The general P2P VoD system framework and the taxonomy of PPLive are instructive for P2P VoD system designs.

In the light of the studies of P2P VoD system designs, a large amount of research on P2P VoD system measurements have been conducted to evaluate the system performance and the user behavior of P2P VoD systems. Yan Huang et al.[2] carried out a large-scale measurement analysis to measure the users' behavior, the effectiveness of the replication scheduling strategies, and the level of user satisfaction. Our previous work [14] collected the traces of PPVA, which has 150 million unique users. We did an in-depth analysis of PPVA's system performance, including server bandwidth savings, acceleration effectiveness as well as client overhead. Jun Lei et al. [3] presented an analytical and experimental study on Joost, and further investigated its peer management in terms of the time pattern, bandwidth consumption and locality considerations. Based on their measurement results, they also provided new suggestions for a better design of the P2P VoD system.

Besides those practical design and measurement studies, there also exist plenty of model analysis studies to make the P2P VoD system more efficient, scalable and robust. Fan B et al. [5] described a fundamental tradeoff that exists among system throughput, sequentiality download and system robustness, and proved that no system could achieve all of them simultaneously. Liu S. [6] analyzed how to provide resources for the streaming system, and derived the performance bounds for the minimum server load, the maximum streaming rate, and the minimum tree depth under different peer selection constraints. Zhou Y et al. [8] described a simple stochastic model that could be used to compare different data-driven downloading strategies, and the trade-off between startup latency and continuity, as well as the methods with which the system scalability can improve continuity. Yuan H and Yunhao L proposed VOVO[15], a VCR-oriented VOD for large-scale P2P networks, it can predict the requested segments based on the information collected through gossips, by mining associations inside each video, and they also designed a collaborative prefetching scheme to optimize resource distribution. These model analyses provide valuable guides for the P2P VoD system optimization. Besides, some researchers also tried to propose standards for the P2P VoD policies[16].

What has been mentioned above includes mainly comprehensive analyses of the P2P VoD system. Many researchers have also finished much research just to study one policy deeply, and proposed plenty of optimization policies to make the P2P VoD system work better. These works are summarized as shown in Table 1. A detailed introduction of these policies will be presented in Section 3.

As we can see, there has been much research working on the P2P VoD system. However, most of them just concentrate on one policy optimization, without any consideration to the cooperation effect of the three policies. Unlike these existing works, our paper concentrates on the two questions proposed in Section 3. In this paper, we will compare the performance of P2P VoD systems with different policy compositions under different circumstances. The impact of resources on policies selection in the P2P VoD system will be studied as well.

3 P2P VoD system analysis and policy introduction

According to the existing system design[2–4, 12], the P2P VoD system usually consists of the following components shown in Fig. 1: (1) Peers that download video pieces from other peers or servers and play the video; (2) Content Servers that have all video files and provide extra upload capacity for clients to improve the service quality and user experience; (3) Trackers that help peers find content servers and other peers which have the replica of the peers' requesting video. There may also be components, for example, an index server (helping peers get the video list and tracker list), NAT (Network Address Translation) transit server (helping peers to connect other peers that locate behind the NAT), and cache servers (improving download efficiency and reducing ISP(Internet Service Provider)'s bandwidth cost). However, they are not the core components of the P2P VoD system.

When a peer joins the P2P VoD system, it first requests the channel profile and the tracker list from the index server, and there are usually thousands of videos provided in the P2P VoD system. Then the peer registers to the tracker server when the user selects one video to watch, and gets a list of other peers that have the replicas of the same video. Every video file is split into many pieces, and the peer can request different pieces of this video from different peers concurrently. Which pieces to request next are determined by the piece selection policy, and which peers to request pieces from are solved by the peer selection policy. It can lead to a great system performance difference when different policies are used. To make the best use of peers' upload bandwidth, the P2P VoD system usually uses MVC(multiple video cache) [2] replica strategy and makes each peer contribute a fixed amount of hard disk storage, rather than just cache the replica of the video being watched. How to manage the video storage, mainly the replica replacement strategy which determines which video to be eliminated when the disk is full, is tightly related to the performance of the system.

According to the analysis above and the previous work summary [2], there are three core strategies in the P2P VoD system: (1) the piece selection policy that determines which piece to be requested next; (2) the peer selection policy that decides from which peer to request the selected piece; (3) the replica management policy which determines how to store and replace the watched videos. Although plenty of research works have been done to study the core policies to improve the performance of the P2P VoD system, including system design work[1, 2, 4], system measurement work[3, 14] as well as model analysis work[5–9], hardly do they delve into the three core strategies together. To conduct research on this topic, we first introduce the possible choices for these three policies respectively.

Table 1 P2P VoD system policy comparison (*GIR* Global information requirement)

Policy	Approaches	GIR	Difficulty	Evaluation
Piece selection	Rarest-first [17]	No	Low	Real system
	Sequential [18]	No	Low	Real system
	Probabilistic method [20]	No	Medium	Simulation
	Window-based Method [19]	No	Medium	Simulation
	Segment random [21]	No	Low	Simulation
Peer selection	Random	No	Low	Real system
	Cascading [22]	No	High	Simulation
	Least loaded first [23]	Yes	High	Simulation
Replica management	Random	No	Low	Simulation
	LRU [2]	No	Low	Real system
	Proportional [2, 24]	Yes	High	Real system

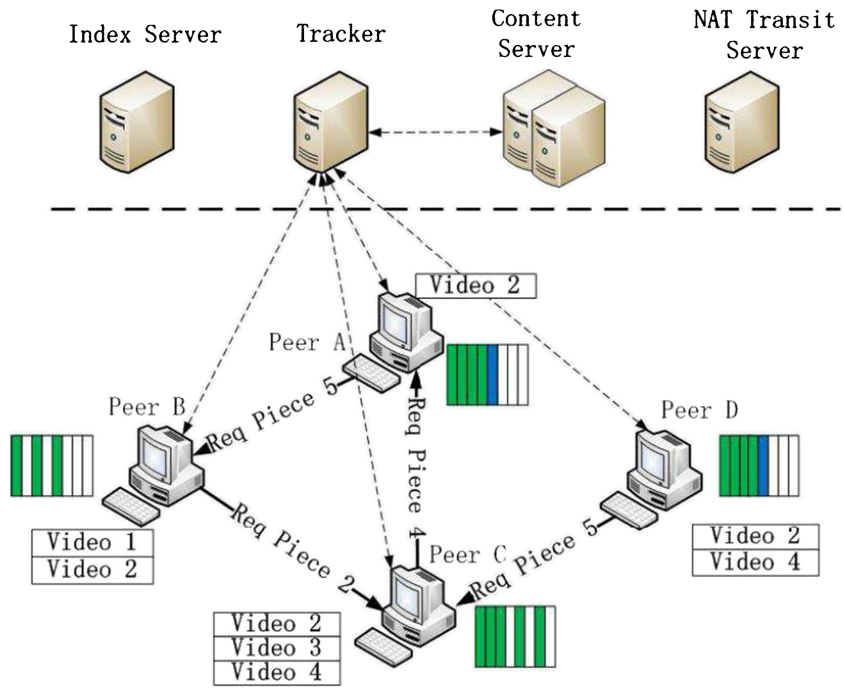


Fig. 1 P2P VoD system framework

3.1 Piece selection policy

The piece selection policy is used to determine which piece to be requested next, and it will guarantee the video's playing continuity and improve user experience. As we have summarized in Section 2, there are several kinds of piece selection policies in the P2P system design, such as the basic random selection strategy, the rarest-first policy [17] used in the P2P file sharing system like BitTorrent, and the sequential [18] policy. The random piece selection policy will just request a random piece that has not been downloaded or requested, the rarest-first algorithm will select the rarest pieces first, while the sequential policy will request pieces of videos from the beginning to the end sequentially.

There are also some other hybrid piece selection policies built on the previous three basic policies. Window-based strategy [19] keeps a slide window which slides as the peer's watching process continues. Then, peers will download the pieces in the window first, and request pieces outside of the window rarest-firstly once all the pieces in the window have been requested. The probabilistic strategy [20] combines the sequential and the rarest-first downloading strategy by using possibility p, and gives higher download possibility p to pieces near the play point. The segment random strategy [21] requests pieces segment by segment sequentially, and the pieces in each segment are requested randomly.

3.2 Peer selection policy

Peer selection policy is used to determine from which peer to request the next piece, and it is closely related to the upload bandwidth resource usage in the P2P VoD system. There are three common peer selection policies for the P2P VoD system design: (1) the random peer selection policy that will request pieces from one random peer with the requesting piece; (2) the cascading peer selection policy [22] that will request pieces from the peer with the requesting piece as well as the least downloading process; (3) the least-loaded-first strategies [23] which will request pieces from the peer with the least uploading load.

The cascading peer selection policy and the least-loaded-first peer selection policy may need extra information exchanges and bandwidth costs, but they can achieve similar effects by using heuristic methods with local information. It should be noted that there are still some research works about how the peer fulfills the piece request directed to itself. We suppose these policies can be switched to peer selection policies and get similar effects. Therefore, we just concentrate on the peer selection strategy in this paper.

3.3 Replica management policy

The replica management policy is used to manage the video replica distribution among different users' disk space, and it determines the replica distribution and the storage space usage in the P2P VoD system. Usually the peers just passively store the video files that they have watched on their disk. Some researchers like [1] also proposed the active replica management policy which made peers replicate the video files, even if the videos are not watched by these peers. In this paper, we just consider the passive replica management policy in the view of the fact that the active replica management policy is complicated and also tends to be resisted against by the users.

The replica replacement strategy is the most important part of the replica management policy. The replica management policy can replace files in video granularity or piece granularity. Here we only consider the policy with video granularity, like PPVA [14]. There are several common video replica replacement strategies used in the P2P VoD system, such as, the random replica replacement strategy, the LRU strategy [2] and the proportional replica distribution strategy [2, 24]. The random replica replacement strategy will abandon one random video file when there is no extra space on a user's sharing disk. The LRU strategy will just abandon the least recently used video files, while the proportional replicas distribution strategy will replace videos according to the availability to demand ratio (ATD) [2] and keep videos replica count proportional to the number of viewers. The proportional replica distribution strategy needs a central node to provide replica information of the system.

We introduce three core strategies in the P2P VoD system in this section, and there are several possible choices for each strategy. It should be noted that we never intend to collect all the possible choices here since there are numerous optimization policies, and that we just select the popular and simple ones here. Although much work on these policies has been done, the system effect of different policy compositions also needs further research.

4 Simulation setup

In this section, we build a simulation framework to compare the effect of different policy choices, as well as the performance of different policy compositions. Theoretical models, real system measurements and system simulations are usually used to analyze the performance of the P2P VoD system. However, it is improper to use theoretical models [5, 6, 8] and real system measurement [3, 14] to conduct research on this topic. It is also difficult to build a theoretical model to analyze the piece selection policy, the peer selection policy as well as the replica management policy at the same time. The performance of different policy compositions is related to many parameters, so a simplified model cannot solve this problem accurately. Besides, the real system measurement is impractical since it is impossible to implement these policies one by one and attract many users to test these systems. Therefore, simulation is the best choice for the preview research on this topic. As for the specific methods, the simulation on PlanetLab is a possible choice, but it will take much overhead and time. Therefore, we build a simulation framework[6] to settle the problem.

To better reflect the real environment, we set the values of necessary factors based on the trace data of PPVA [14]. The important factors include network bandwidth, sharing storage space, number of peers, watching preference of users, video popularity, replica distribution, etc., and we will demonstrate the related factors in the rest of this section.

Similar to the design space analysis for the incentive mechanisms in [10], five piece selection policies, three peer selection policies, as well as three replica management policies listed in Table 1 are implemented in our simulation framework. In each round of the simulation, peers can choose one piece selection policy, one peer selection policy and one replica management policy, and then combine the chosen policies as the peer's core strategies. In addition to the strategies, there are still some other factors that may bring influence on the performance of the P2P VoD system, such as, the network bandwidth and sharing storage space of peers, the number of peers and videos, and even the watching preference of users. In our simulation, we also take these factors into consideration. The overall design of our simulation is shown in Fig. 2. There are three main components in our simulation: movies, peers and the P2P VoD system. Different strategies are decoupled as functions in the P2P VoD system. The major notations are listed in Table 2.

In our simulation, we assume that network delay is 0 for simplicity.[7] The total simulation time is split into lots of time unit τ. We use t to represent time interval $[t\tau,(t+1)\tau]$, $t=0,1,2\ldots$, and assume that the peers start requesting new pieces at $t\tau$ and finish downloading them in one time unit τ. New peers will join the system at $t\tau$, $t=0,1,2\ldots$, and leave the system at $(t+1)\tau$, $t=1,2,3\ldots$. Assume that there are M videos in the P2P VoD system, and each video has P pieces and the size of each is 1 with play time $t=\tau$. Hence, in the simulation, one piece will be downloaded or played in one time unit. It is feasible in practical systems if we set the piece and time unit to a proper size.

N peers, with some storage space filled with replicas, exist in the P2P system at the beginning of our simulation. New peers will join the system with possibility R_j=0.1 in each round. Peers that have not finished watching their videos will leave the system with possibility R_l=0.5, and peers in the P2P VoD system that have finished watching one video will leave the system immediately or stay in the system for another video with possibility R_f=0.5 and 1-R_f, respectively. New peers have no video replica on their disks and will request a new video to watch from the beginning when they join the system. Peer's download and upload capacity are D and U, respectively, and both are integral multiples of a piece size. Therefore, peers can download at most D pieces in a time unit. Their sharing disk

[6] The code of our simulation is shared at http://code.google.com/p/p2p-vod-simulation/

[7] In fact, network delay may have a mandatory influence in peer connections and the simulation results.

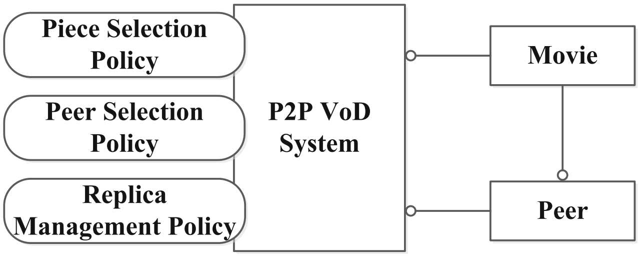


Fig. 2 Simulation structure

space is S which is the integral multiple of the video size. New peers will start playing the video after downloading 10 pieces. In the practical VoD system, most users will watch just a few popular videos [14, 25]. More precisely speaking, the top 10 % popular videos account for 82 % watching, and the top 20 % account for 94 % in PPVA. In our simulation, we just use the Pareto principle[8] to simulate the video popularity. That is, peers will choose the top 20 % videos with 80 % possibility and the rest with 20 % possibilities.

In our simulation, we use peer's delayed pieces count to indicate the performance of the P2P VoD system. It can reflect the most important goal of the system, namely, the playing continuity of users. For piece k, we can calculate its required download completion time $t_r=t_s+k-s$, where t_s is the time when a peer starts watching a video, and s is the corresponding piece.[9] Moreover, the download time t_d of piece k can be recorded in our simulation, and the downloading of piece k is delayed if $t_d < t_r$. The delayed piece count of a peer watching a video is the number of the delayed pieces in the process of video watching. Peer's delayed piece count distribution is used as the metric of the system performance.

To compare the performance of different policies and policy compositions, seven series of simulation are implemented by using different download, upload and storage capacities, respectively. In each series of simulation, there are 5*3*3=45 rounds of simulations using different strategies. The seven scenarios used in our simulation framework are shown in Table 3 with different networks and storage conditions. The heterogeneous scenario has two kinds of peers: the peers with limited bandwidth and just enough replica space (D=1, U=1, S=1) and the peers with sufficient bandwidth and replica space (D=2, U=2, S=4).

The performance of different policy compositions under different network bandwidth and storage conditions is measured after the 45*7 rounds of simulation, and we will analyze the simulation result in the next Section.

Table 2 Summary of main notations

Symbol	Illustration
N	Number of initial peers
M	Number of shared videos
P	Piece number of each video
D	Peer's download capacity
U	Peer's upload capacity
S	Peer's sharing disk space
R_j	New peer's join rate
R_l	Peer's leave rate before finishing watching
R_f	Piece number of the shared file
τ	Time unit
$t=\tau$	Play time of each piece
T	Simulation time

Table 3 Simulation scenarios summary (*DC* Download capacity, *UC* Upload capacity, *SC* Storage capacity)

Scenarios	DC	UC	SC
Bandwidth limited scenario without extra replica space	1	1	1
Bandwidth limited scenario with limited replica space	1	1	2
Bandwidth limited scenario with sufficient replica space	1	1	4
Bandwidth sufficient scenario without extra replica space	2	2	1
Bandwidth sufficient scenario with limited replica space	2	2	2
Bandwidth sufficient scenario with sufficient replica space	2	2	4
Heterogeneous scenario with different kinds of peers	1 or 2	1 or 2	1 or 4

5 Simulation result analysis

Based on our simulation framework, we analyze our simulation results in this section. The count of delayed pieces is used as the only metric to compare the effect of different policy compositions under different circumstances. During our simulation, we first make two of the three core policies (the piece selection policy, the peer selection policy and the replica management policy) as the fixed input, and then compare the performance of different possible choices for the rest policies. Then, we compare the effect of different policy compositions under different circumstances. The importance of different system resources is also analyzed when different circumstances are considered. The scalability of the P2P VoD system is also analyzed by changing the number of peers and movies. In the end, further discussion and comparison with other works are presented.

[8] http://en.wikipedia.org/wiki/Pareto_principle

[9] Peers may be in the process of watching video at the beginning of simulation, so the start piece could not be 0.

5.1 Different single policy performance comparison

In our simulation, we choose five possible methods for the piece selection policy, three for the peer selection policy and three for the replica management policy as listed in Table 1. In this subsection, the performance of different piece selection policies, different peer selection policies and the replica management policies in different scenarios are compared. In the simulation, we assume that the initial peer count N=1000, the sharing video count M=100 and the new peer joining rate R_j= 0.1 in the P2P VoD system. When we look closely into one policy, the other two policies will just use one selected policy as input.

5.1.1 Comparison of piece selection policies

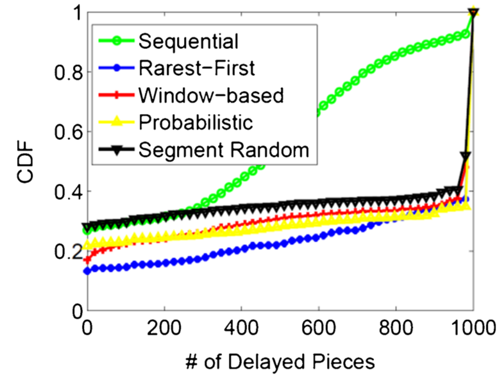
To compare different piece selection policies, our simulation changes the piece selection policy and measures the performance of the P2P VoD system under different circumstances. In the simulation, we use the simplest random peer selection policy and random replica management policy as the default peer selection policy as well as the replica management policy. The delayed piece count distribution of peers with different piece selection policies in different scenarios is shown in Fig. 3.

It is obvious that the sequential policy will achieve the best playing continuity with the least missed pieces under all circumstances. The rarest-first policy has the worst performance in all scenarios. As for the other three policies, their missed pieces count cumulative distribution lines lie between those of the sequential policy and the rarest-first policy. When the bandwidth resource is limited, the other three policies will have the performance similar to the rarest-first policy and be much worse than the sequential policy, but will have the effect similar to the sequential policy when the bandwidth resource is sufficient in the P2P VoD system. In general, the sequential policy is definitely the first choice for the piece selection policy of the P2P VoD system.

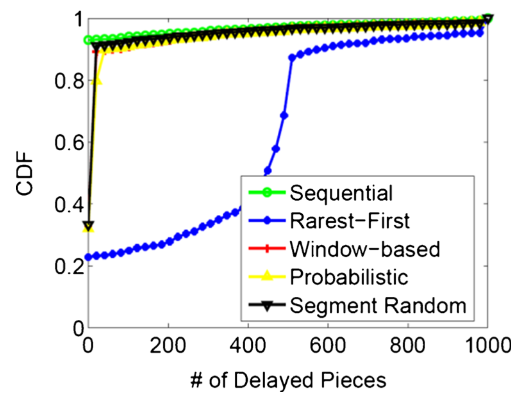
5.1.2 Comparison of peer selection policies

In the simulation, the peer selection policy changes in the simulated P2P system while the sequential policy and the random policy are used as the piece selection and the replica management policy respectively. The performance of different peer selection policies is compared by using peers' delayed pieces count.

Figure 4 indicates that the performance of different peer selection policies does not have as many differences as that of different piece selection policies. When the bandwidth resource of the P2P VoD system is limited, the cascading peer selection policy will have better performance than the other policies, since the cascading peer selection policy will select



(a) Scenario with Limited Bandwidth and No Extra Storage



(b) Scenario with Limited Bandwidth and Sufficient Storage

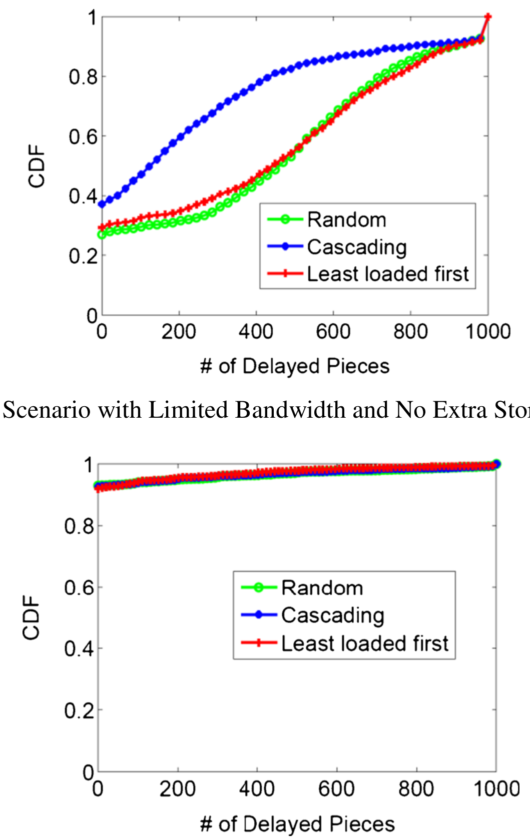
Fig. 3 Comparison of piece selection policies' performance **a** Scenario with limited bandwidth and no extra storage **b** Scenario with limited bandwidth and sufficient storage

peers by using the scheduling algorithm to make the best use of peers' upload bandwidth. When the bandwidth resource is limited, the cascading policy will have less performance advantages in storage-sufficient scenarios than that in scenarios with no extra storage. All in all, the cascading peer selection policy will be the best for the P2P VoD system.

5.1.3 Replica management policy comparison

To evaluate the performance of different replica management policies, the performance of the P2P VoD system with different replica management policies is compared, and the simulation uses the sequential downloading policy and the cascading policy as the default piece and peer selection policies.

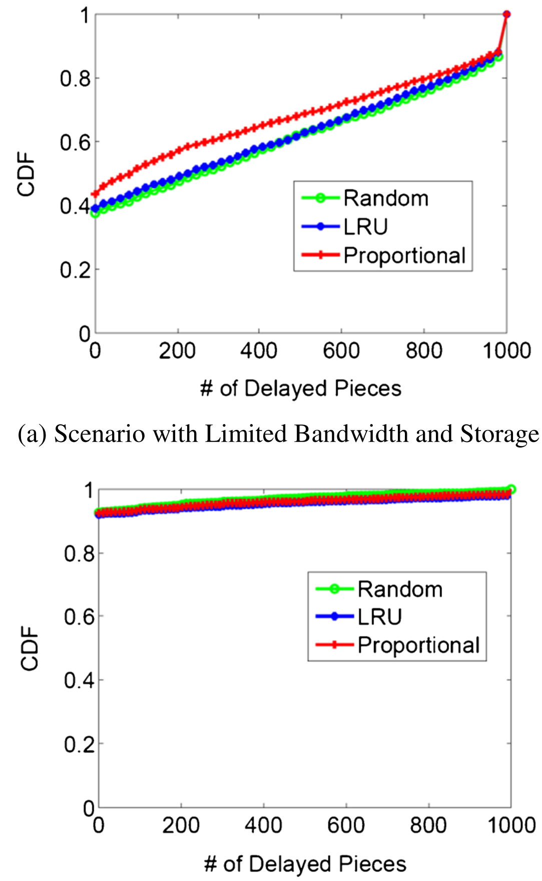
Similar to the peer selection policy, the simulation result in Fig. 5 shows that the performance of different replica management policies has similar effects when the bandwidth resource is sufficient. When the system's bandwidth resource is limited, the proportional replica management policy has better performance than the random policy as well as the LRU policy. The proportional policy will keep the optimal replica distribution among peers so that it can make the best use of peers' bandwidth and storage resources. As the storage



(a) Scenario with Limited Bandwidth and No Extra Storage

(b) Scenario with Sufficient Bandwidth and Sufficient Storage

Fig. 4 Comparison of peer selection policies' performance **a** Scenario with limited bandwidth and no extra storage **b** Scenario with sufficient bandwidth and sufficient storage



(a) Scenario with Limited Bandwidth and Storage

(b) Scenario with Limited Bandwidth and Sufficient Storage

Fig. 5 Comparison of replica management policies' performance **a** Scenario with limited bandwidth and storage **b** Scenario with limited bandwidth and sufficient storage

space grows, the proportional replica management policy will have less advantages than the other two policies.

It should be noted that the LRU policy has the effect similar to the random policy in our simulation since we do not consider the fact that the video popularity changes [26] during the simulation. If the video popularity variation is introduced, the LRU replica management policy will have better performance than the random policy.

The single policy performance comparisons above all indicate that there is little difference among different policy choices if the bandwidth and storage resources are sufficient, and the performance difference will decrease as the resources grow. Therefore, if the network bandwidth and the sharing disk space of peers are enough, the playing continuity of peers will achieve the best effect even if we just use the simplest piece selection, peer selection and replica management policies. There will be more performance differences among different piece and peer selection strategies than that of replica management strategies. Hence, we believe that it will be more effective to optimize the piece and peer selection strategy than the replica management strategy.

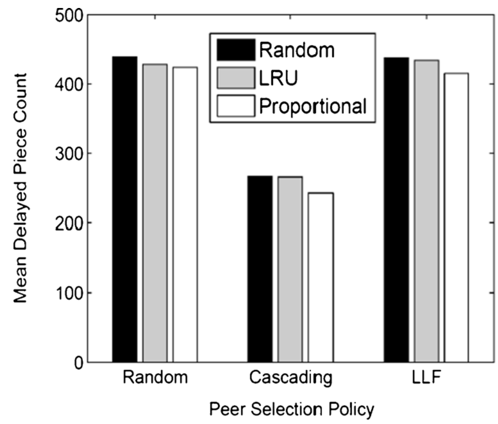
5.2 Comparison of different policy compositions' performance

The performance of different choices for the piece selection policy, the peer selection policy as well as the replica management policy areis compared in the last subsection. According to the previous simulation results, the sequential policy is definitely the best choice for piece selection policy since its performance is much better than that of other policies. For the peer selection and the replica management policy, there are not so many differences between different policies, especially when the bandwidth and storage resources are sufficient in the P2P VoD system. In this subsection, the performance of the P2P VoD system with different policy compositions will be simulated. Since the sequential policy is the best choice for the piece selection policy, we keep using the sequential piece selection policy and change the peer selection and the replica management policy. In Section 3, we have showed that there are 3 possible choices for the peer selection and replica management policies respectively in our simulation; hence, the performance of 9 compositions as a whole is measured in our simulation.

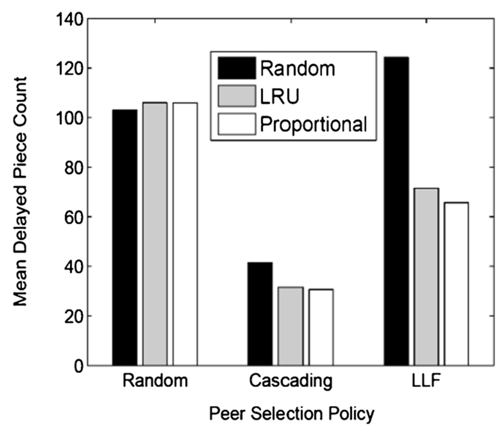
Two scenarios are considered in the simulation, which refer to the resources-limited scenario (D=1, U=1 and S=2), and the resources-sufficient scenario (D=2, U=2 and S=4).

The mean delayed pieces count of peers in P2P VoD systems with different policy compositions are shown in Fig. 6. The three sets of bars in each subfigures of Fig. 6 indicate the performance of different systems with different peer selection policies, while the three bars in each set shows the performance of different systems with different replica management policies. Figure 6(a) shows the performance of different P2P VoD systems with different policy compositions when resources are limited. It is obvious that the system with the cascading peer selection policy has much less mean delayed pieces counts than the other two peer selection policies, and that the system with the cascading peer selection policy and the proportional replica management policy has the best

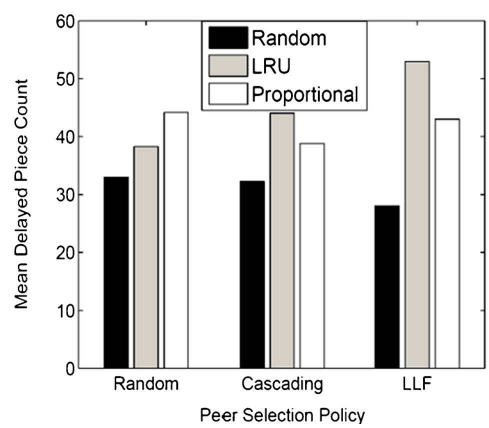
Fig. 6 System performance comparison with different policy composition **a** Performance comparison in scenarios with limited resources **b** Performance comparison in scenarios with heterogeneous resources **c** Performance comparison in scenarios with sufficient resources



(a) Performance Comparison in Scenarios with Limited Resources



(b) Performance Comparison in Scenarios with Heterogeneous Resources



(c) Performance Comparison in Scenarios with Sufficient Resources performance. The simulation results in the scenario with sufficient resources are presented in Fig. 6(c). We can see that there is little difference between different policy compositions when the resources are sufficient. In the heterogeneous scenario where the number of peers with sufficient resources equals to that of peers with limited resources, the performance results are similar to those of the resources-limited scenario, and there is less difference between different compositions than that between the resource-limited scenario. Therefore, the composition with the cascading peer selection policy, the proportional replica management policy as well as the sequential piece selection policy has the best performance, which is consistent with the conclusion in the previous Subsection.

5.3 The importance of different resources

In the P2P VoD system, there are two kinds of resources closely related to the performance of the system. That is, peers' bandwidth and its storage space. Peers' bandwidth, namely, their downloading and uploading capacity, can affect the sharing rate of videos and the playing continuity of peers. Peers' sharing disk space is directly related to the number of the videos' replica in the P2P video system. Therefore, peers' bandwidth and storage capacity are the most important resources in the P2P VoD system. In this section, the importance of these resources will be analyzed.

First, the system performance is measured by using different downloading and uploading capacity in no-storage scenario and sufficient storage scenario respectively. In the measurement, the peers of the P2P VoD system use the sequential piece selection policy, the cascading peer selection policy and the proportional replica management policy respectively. The measurement results show that the system performance will improve as the downloading and uploading capacity increases. However, there will be less improvement by merely increasing the bandwidth capacity when the storage space shared by peers is limited. In Fig. 7, the P2P VoD system with D=2 and U=1 has the performance similar to that in the bandwidth-limited scenario (D=1, U=1). In storage sufficient scenarios, the performance of the system will always improve as the downloading capacity or uploading capacity grows.

Secondly, we simulate different P2P VoD systems with different storage space in two scenarios, in the first one of which the bandwidth is limited (D=1, U=1) and in the second one the bandwidth is sufficient (D=2, U=2). The sequential policy, the cascading policy and the proportional policy are chosen as the piece selection policy, the peer selection policy and the replica management policy respectively. According to our simulation results shown in Fig. 8, the system performance will increase if the storage space increases. When the bandwidth resource is sufficient, the performance of the P2P VoD system will have little improvement as the storage space grows.

In summary, the system performance will increase with the resource growing. However, it will have little effect if the system increases bandwidth only when the storage is limited. The simulation result also shows that there will be little difference even though the storage space is increased if the bandwidth resources are sufficient. Therefore, theoretically the P2P VoD system can work well without extra replica space as long as the bandwidth of peers are large enough. However, the extra storage space can help improve the performance of the system in practical scenarios where the peers' bandwidth is limited. In the real system, both the cost and the collaboration of different resources should be considered to achieve more edge effect.

In addition, the performance of heterogeneous system will decrease as the percentage of peers with limited resources grows in the P2P VoD system, just as Fig. 9 shows. However, our simulation results also give evidence that there will be no performance difference if the percentage of peers with limited resources is small. In our simulation, the mean delayed pieces count stays at a low level when the percentage of peers with limited resources is below 40 %. Therefore, in the practical heterogeneous environment, the P2P VoD system can work well as long as the majority of peers have sufficient bandwidth and storage resources. The further discussion of the resources in the P2P VoD system will be provided in the next Section.

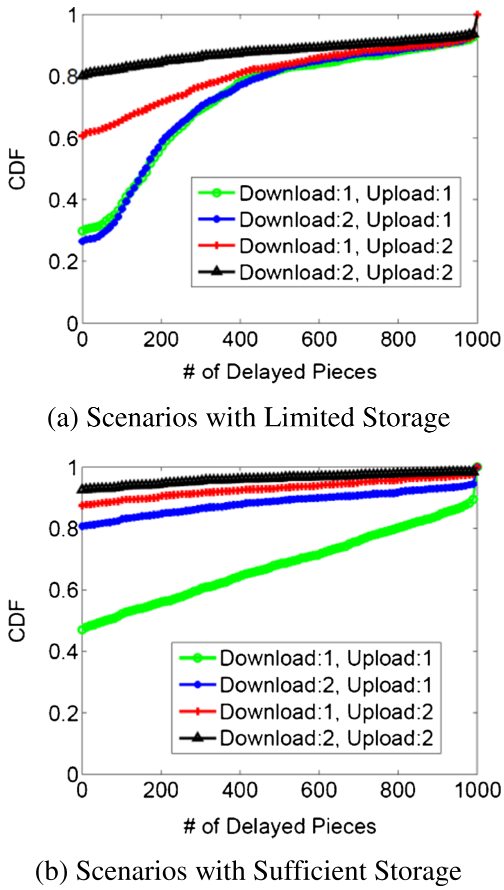
5.4 Further discussion of resources in the P2P VoD system

To improve the users' playing continuity and reduce the servers' uploading bandwidth usage, the peers should provide more uploading bandwidth for each other. To achieve this goal, either the peers get more uploading bandwidth, or the system improves the uploading bandwidth usage ratio. Peers can provide extra storage space to improve its uploading bandwidth usage ratio, since peers with more video replicas can be requested by more peers.

In this section, we will further analyze the importance of the resource in the P2P VoD system, aiming to find the relationship between the bandwidth and storage resources. In the model, we assume that the downloading and uploading capacity of all peers are D and U respectively. Peers storage space is S, which means a peer can store at most S videos. In the P2P VoD system, there are M peers and N videos with Q pieces, and each videos playing rate is P. We will discuss different circumstances in the P2P VoD system.

5.4.1 Unconstrained steady state system

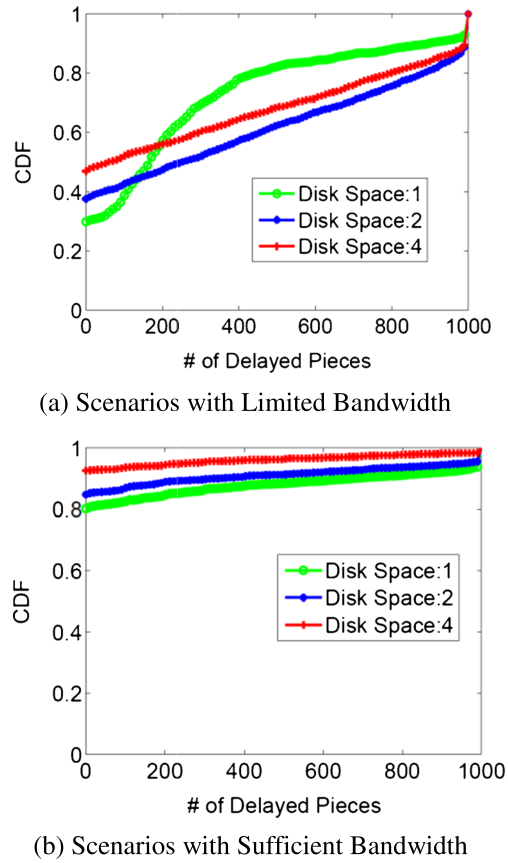
In the unconstrained steady state system, the connection between peers is full mesh, and the peers watching process is uniformly distributed to all the videos. In the steady state system, assume that the peers' uploading bandwidth is shared by S videos. Then, to make sure every video can play smoothly, the downloading and uploading capacity should fulfill the



(a) Scenarios with Limited Storage

(b) Scenarios with Sufficient Storage

Fig. 7 System performance comparison with different bandwidth **a** Scenarios with limited storage **b** Scenarios with sufficient storage



(a) Scenarios with Limited Bandwidth

(b) Scenarios with Sufficient Bandwidth

Fig. 8 System performance comparison with different storage **a** Scenarios with limited bandwidth **b** Scenarios with sufficient bandwidth

following requirement:

$$\frac{N}{M} * P \leq \frac{N * S}{M} * \frac{1}{S} * U + \frac{L}{M}$$

Namely,

$$L \geq (P - U) * N$$

It means that the server bandwidth just needs to fill the gap between the video playing rate and uploading capacity of all the peers. If the peers uploading capacity is larger than the playing rate of the video, no extra server bandwidth is needed. The storage space of peers has no effect on the improvement of the peers uploading bandwidth usage in the steady state system, as long as the peer selection is good enough. In the steady state situation, peers can select neighbors to request pieces through the cascading policy, and then all the peers' uploading bandwidth can be used except the uploading bandwidth of the peers with the least downloading process. That is, only $1/Q$ peers uploading capacity is wasted. Since a video usually has a large number of pieces, the wasted uploading bandwidth can be ignored.

5.4.2 Constrained steady state system

In the constrained steady state system, one peer can establish a connection with at most K neighbors which have the watching video replica. The P2P VoD system can be treated as a directed graph, where the sum of peers in-degree equals to the sum of peers out-degree. Hence, for a peer, K peers on average will request video pieces from it on average. The peers' uploading bandwidth is shared by S videos uniformly. For a peer who watches a given video, the

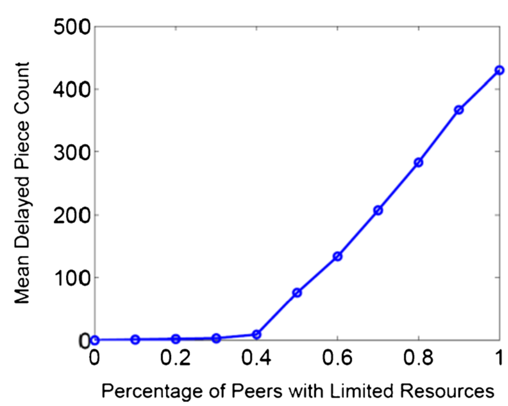


Fig. 9 The performance of heterogeneous system

following inequality should be satisfied:

$$P \leq \frac{U}{S} * \frac{K * S}{K} + \frac{L}{N}$$

We can get the same result under the unconstrained steady state situation. Hence, the storage space is not necessary. If no storage space is provided, the uploading bandwidth usage ratio in the beginning of the peer selection process is

$$R = 1 - \left(1 - \frac{P}{Q}\right)^K$$

R refers to the ratio where K neighbors downloading process is faster than itself, so that the peer can not provide pieces for the neighbors. In the formula, p is the downloading process of the peer. The neighbor constraint is usually 30 in practical P2P VoD systems like PPLive. The uploading bandwidth usage changes as the downloading process changes, as Fig. 10 shows. We can see that, when the downloading process occupies more than 10 %, then there will be just 5 % possibility that the uploading bandwidth is wasted. In the downloading process, the peers can replace its neighbors dynamically and build a cascading link to make best of the upload bandwidth.

5.4.3 *Unconstrained flash-crowd system*

In the unconstrained flash-crowd system, peers join the P2P VoD system and watch some videos simultaneously, and the connections between peers are a full mesh. In the flash-crowd state, peers are not able to upload pieces to the peers who watch the same video; hence, those peers uploading capacity will be wasted if no extra replica is stored. On the other side, in the flash-crowd state, peers can not get enough uploading resources from the peers who watch the same video.

To fulfill peers downloading requirement, the downloading and uploading capacity for every video should fulfill the following requirement:

$$\frac{N}{M} * P \leq \frac{N * (S-1)}{M} * \frac{1}{S-1} * U + \frac{L}{M}$$

Namely,

$$L \geq (P-U) * N$$

Hence, we get the same conclusion in the unconstrained steady state system. The storage space of peers can help to improve the peers uploading bandwidth usage in the flash-crowd system. But if full-mesh connections are provided in the system, only one piece of extra storage space for storing one video is needed.

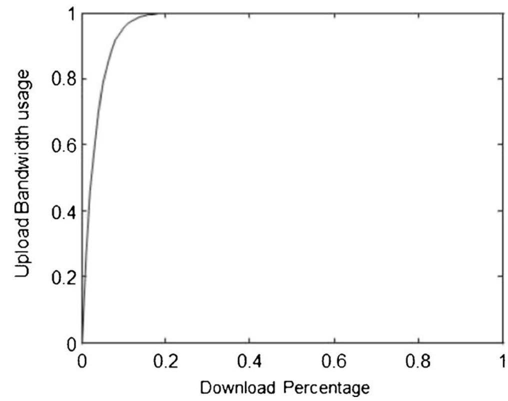


Fig. 10 The upload bandwidth usage changes as peer's download process

5.4.4 *Constrained flash-crowd state system*

In the constrained flash-crowd system, peers join the P2P VoD system and watch some videos simultaneously, and a peer can establish a connection with at most K peers.

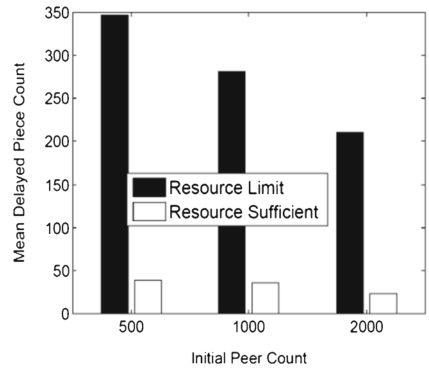
To make the best use of peers uploading bandwidth, the peer should store some video replica on its disk. On average, K peers will connect a give peer A. For every video, there will be $K/(S\text{-}1)$ peers connected to peer A. For every connected peer, it will take possibility $1/K$ to request one piece from peer A. Then there will be $1/(S\text{-}1)$ peers requesting some pieces of each video from peer A. Hence, there will be one peer requesting pieces from peer A on average, no matter how much storage space is provided. Hence, the storage space of peers can help to improve the peers uploading bandwidth usage in the flash-crowd system. But only one extra storage space to store one video is needed.

All in all, to get better playing continuity and reduce server bandwidth usage, the P2P VoD system should either increase uploading bandwidth or improve the peers' upload bandwidth usage ratio. However, through our analysis, the performance increase brought by storage space is limited. Hence, the system provider should put more emphasis on increasing bandwidth to provide better streaming service.

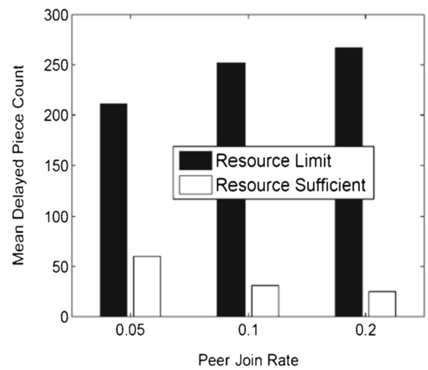
5.5 Robustness and scalability of different policies

Robustness and scalability are also important requirements of the P2P VoD system. In our simulation, the initial peer count N, the peer join rate R_j and the video count M can be changed. In this subsection, the performance of the system with different peers and different videos will be compared to study the characteristics of the P2P VoD system. Only the simulation results with limited bandwidth and storage resources(D=1, U=1 and S=2) are presented.

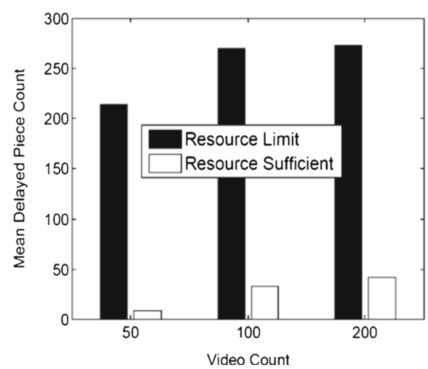
Fig. 11 System scalability analysis **a** Performance comparison in scenarios with different initial peer count **b** Performance comparison in scenarios with different peer join rate **c** Performance comparison in scenarios with different video count



(a) Performance Comparison in Scenarios with Different Initial Peer Count



(b) Performance Comparison in Scenarios with Different Peer Join Rate



(c) Performance Comparison in Scenarios with Different Video Count

Figure 11(a) shows the performance of the P2P VoD system with different initial peer count N under different scenarios. The results prove that the performance of the system will increase as the number of peers increases. Figure 11(b) indicates that the system performance will decrease if more fresh peers without video replicas join the system, and Fig. 11(c) shows that the quality of service provided by the P2P VoD system will decrease as the number of video grows in the system. A large number of videos will lead to low sharing efficiency since there are lots of small swarms and it is difficult to dispatch the resources to many swarms efficiently.

Table 4 Simulation scenarios summary

P2P VoD system	Piece selection policy	Peer selection policy	Replica management policy
Our results	Sequential	Cascading	Proportional
PPLive [2]	Sequential	Least loaded first	Proportional (ATD)
PPVA [14]	Sequential	Least loaded first	Proportional (ATD)
GridCast [1]	Sequential	Least loaded first	Active replication algorithm

5.6 Simulation result discussion

According to the simulation analysis above, the sequential piece selection policy, the cascading peer selection policy and the proportional replica management policy are the best choices for the P2P VoD system. We compare our simulation results with the existing system design work as shown in Table 4.

Our simulation results suggest the same piece selection policy and the replica management policy as PPLive [2] and PPVA [14]. As for the peer selection policy, the practical P2P VoD systems usually use the least loaded first policy which will select the peers with the best connection, and this policy can adapt itself to work well on the real Internet with heterogeneous bandwidth condition self-adaptively. However, the cascading peer selection policy can work well under a bandwidth constraint condition through global or heuristic scheduling. Generally speaking, the comparison with the practical system design reflects the validity of our simulation results.

6 Conclusion

The piece selection policy, the peer selection policy and the replica management policy are the core strategies in the P2P VoD system. In this paper, we provide evidence that the sequential piece selection policy, the cascading peer selection policy and the proportional replica management policy are the best choices when the bandwidth and storage resources are limited, and their composition also has the best performance. However, there are not many differences among different policy choices when the bandwidth and storage resources are sufficient. In addition to these results, our simulation results also indicate that the P2P VoD system can work well without extra replica space as long as the bandwidth of peers are large enough. However, the extra storage space can help improve the performance of the system in practical scenarios where the peers' bandwidth is limited.

In this paper, we only compare the popular and feasible policies, but more possible policies should be studied in the future. Although the network condition and video popularity variation are not taken into consideration in our simulation, these factors may lead to a different result. Therefore, a more complicated and practical simulation has been put into our agenda for future research, and the simulation should include more aspects into consideration, for example, network topology configurations, network delays, and node distribution patterns.

Acknowledgments This work has been supported in part by NSFC Projects (61170292, 61272446), National Science and Technology Major Project (2012ZX03005001), 973 Project of China (2009CB320501 and 2012CB315803) and National Key Technology R&D Program (2011BAK08B05-02).

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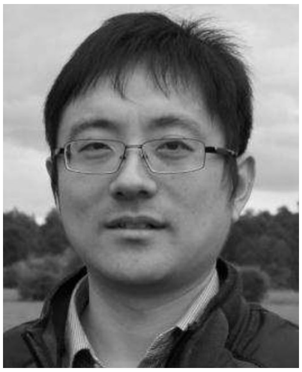
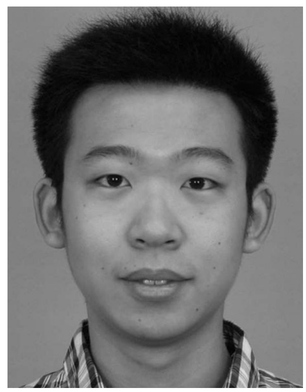


Ke Xu received his Ph.D. from the Department of Computer Science of Tsinghua University. He is currently a full professor in the Department of Computer Science of Tsinghua University. He has published more than 100 technical papers and holds 20 patents in the research areas of next generation Internet, P2P systems, Internet of Things(IoT), network virtualization and optimization. He is a member of ACM. He has guest edited several special issues in IEEE and Springer Journals. He is serving as associate editor of Springer journal Networking Science. (email: xuke@tsinghua.edu.cn)

Xin Liu received his M.S. degree in Computer Engineering from San Jose State University. He is currently working toward the Ph.D. degree in the Department of Computer Science and Technology, Tsinghua University, China. His research interests include network architecture, Internet of Things and QoS.

Zhen Ma received the BEng degree in computer science from Beijing University of Posts and Telecommunications and the M.S. degree from the Department of Computer Science of Tsinghua University. He is now an engineer at Google Inc, CA, USA. His research interests include P2P and overlay network. (email: buptmazhen@gmail.com)



Yifeng Zhong received the BEng degree in software engineering from Tianjin University, China in 2011. Currently he is a Ph.D student in the department of computer science of Tsinghua University. His research interests include P2P network and Internet economics. (victorzhyf@gmail.com)

Wenlong Chen born in 1976, Ph.D.. His research interests include network protocol and network architecture. (email: wenlongchen@sina.com)