Cooperative Traffic Management for Video Streaming Overlays

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Abstract

Peer-to-Peer (P2P) based overlays often ignore the boundaries of network domains and make traffic management challenging for network operators. Locality-aware techniques are a promising approach to alleviate this impact, but often benefit only network operators and fail to provide similar benefits to end-users and overlay providers. This is especially severe with video streaming overlays that are responsible for large amount of Internet traffic. In this paper we present and evaluate a collaborative approach where a network operator measures the behavior of overlay users and promotes a subset of them in terms of up- and download bandwidth. This creates an incentive to users and overlay providers to cooperate by using locality awareness according to the operator's policies. We evaluate our approach both with a real application and via extensive simulations to analyze the user selection metrics and the impact on different network operators. Our study shows that this cooperative traffic management approach leads to a situation that is beneficial for users, content providers, and network operators.

Keywords: peer-to-peer, ISPs, locality, traffic management, video streaming

1. Introduction

Video streaming is emerging as one of the most popular services in the Internet. It comprises a large set of different applications ranging from video communications over live streaming to video-on-demand (VoD). According to the Cisco Visual Networking Index[1], video traffic contributes today already more than 33% of the total consumer Internet traffic and this fraction is predicted to grow to 91% by 2014.

Video applications constitute a major challenge for content providers and network operators since they require a high amount of network resources in order to deliver a good quality-of-experience and to satisfy the users' expectations. A promising solution to this problem is peer-assisted video streaming where users watching a video also upload parts of the video to other users in a peer-to-peer (P2P) based manner. This reduces the load on the video servers and makes those systems more scalable in terms of the number of concurrent users that can be served [2, 3, 4].

Due to the high amount of traffic produced by video applications, the need for a reasonable management of such traffic arises for network operators. The most prominent solution for that problem is locality awareness, which is currently under discussion in the IETF working group on application layer traffic optimization [5]. Locality awareness equips peers with the knowledge about the topology of the underlying physical network and/or preferences of the operator to enable a "better-than-random" peer selection for data exchange. This approach has been shown to be highly beneficial for the network operators [6, 7] since a large fraction of the costly inter-domain traffic can be saved. However, there is no clear benefit of applying locality awareness for the users and the content providers. In most scenarios, the performance from the users point of view is not improved [6, 8] or may decrease depending on the concrete implementation of locality awareness and overlay characteristics [9]. This is a severe drawback, which might also slow down or even inhibit an Internet-wide deployment of such mechanisms.

This problem is addressed by a measurement-based optimization approach that we proposed in [10]. Its intention is that operators yield some of their benefits to network-friendly users that apply locality awareness. Those users, which we call highly active peers (HAP), can be identified by the operator through network measurements. To reward them for being network-friendly, the operator can offer faster Internet access for them, i.e., increase their upload and download capacities. Content providers also profit in this case since their users can share more traffic among themselves, which relieves the load on the servers. Therefore, content providers have an incentive to implement locality-aware mechanisms in their clients. In summary, this traffic management scheme, which is based on voluntary cooperation of all involved parties, facilitates a triple-win situation for network operators, users, and content providers.

In this paper, which is an extended version of [10], we refine our original proposal, present a prototype im-

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plementation, and conduct a comprehensive performance evaluation of our cooperative traffic management approach based on simulations and testbed experiments with a prototype. Our evaluation uses a mesh-based VoD overlay and comprises the HAP promotion as well as locality awareness mechanisms. It shows that the combination of HAP promotion and locality awareness indeed leads to the desired triple-win situation for network operators, content providers, and users. For that purpose, we extend our previous work [10] in the following ways. (1) We propose and compare different metrics, which can be measured by network operators, to select peers to be promoted to HAPs. Their performance is evaluated in a simulation study comprising 50,000 peers and 2,500 video files. (2) We introduce a prototypical implementation of the proposed HAP promotion mechanism in the German Lab testbed and assess the impact of the traffic management on all three stakeholders. To that end, we adapt locality awareness mechanisms for file-sharing to video streaming and implement them in the Tribler streaming client [11] that we used for our experiments. (3) As shown in our previous work the HAP promotion mechanism might lead to an undesired increase in outbound traffic, especially for early adopters. We introduce a technique to avoid such an increase and demonstrate its effectiveness. (4) Finally, we compare the performance of HAP promotion to other management approaches for P2P traffic such as blocking and caching.

The paper is structured as follows. Sect. 2 presents background information and discusses related work. In Sect. 3, we introduce our cooperative traffic management approach. The first part of our performance evaluation based on testbed experiments with real clients in a single swarm is presented in Sect. 4. In Sect. 5, we extend the scenario to a large number of swarms and investigate it via simulations. Finally, we conclude our paper in Sect. 6.

2. Background and Related Work

In this section we describe the state-of-the-art for the traffic management of overlay applications. Then, we review P2P-based VoD services.

2.1. Overlay Traffic Management

The largest incentive to apply overlay traffic management exists for network operators. Their goal is to reduce inter-domain traffic, which may be costly due to inter-provider agreements. Therefore, the earliest traffic management approaches, namely traffic shaping or blocking, are unilateral mechanisms implemented by the network operators. However, these measures reduce the performance of the overlay and lead to dissatisfied users [12]. An alternative approach, which does not reduce the overlay performance, is the use of P2P caches. These caches can serve the requests of local peers and reduce incoming traffic in this way [13]. However, this advantage comes at the price of the resources the network operator has to provide for the caches, the effort to support different protocols, and may also raise legal issues.

Finally, a traffic management approach that has received much attention recently is locality awareness [14, 15]. Here, the overlay structure is modified to prefer short, local connections over longer and more costly inter-domain connections. The required information can be obtained via an operator provided oracle [7] or an iTracker [16], be derived from the DNS redirection behavior of content distribution networks as proposed in [17], or be based on BGP routing tables [18]. At the P2P client this can be implemented by the so-called Biased Neighbor Selection (BNS) [6], as well as by Biased Unchoking (BU) [8]. The former changes the mechanism for establishing overlay connections, the latter the selection of peers to upload content to. BNS and BU have been developed primarily with BitTorrent in mind and therefore work with any BitTorrent-based overlay, such as the overlay we use in our performance evaluation. Results from prior evaluations of these mechanisms show that they can reduce inter-domain traffic significantly under certain conditions, while the performance is not reduced from an average user's point of view [19]. However, under realistic conditions a subset of the users might experience negative effects from locality awareness [9, 20]. Thus, there are no clear incentives for an end-user to use a locality-aware system.

In this work, we compare the effect of locality awareness with a new approach, namely the assignment of additional capacity to highly active peers, and show that the combination of these approaches is beneficial for all three stakeholders.

2.2. P2P Video Streaming Overlays

The approach of a P2P overlay supporting dedicated video-on-demand streaming servers and its potential for load reduction on these servers have been evaluated in the recent past [21]. However, the focus is commonly on the benefits for the content provider, without taking into account the effects on traffic management and on the end-user.

A BitTorrent Assisted Streaming System for VoD (BASS) is one of early approaches that extends BitTorrent to support streaming [2]. In the investigated scenario the necessary streaming server bandwidth can be reduced by one third through the support of a P2P overlay. In [3], Vlavianos et al. present and evaluate an enhanced BitTorrent video streaming protocol named BiToS. Toast is another BitTorrent-based support scheme for VoD servers as presented in [4]. Similar to BASS, it shifts load from the dedicated VoD servers to a BitTorrent overlay, with parts of the video that cannot be delivered by the overlay being requested from the server. Again, the focus is on overlay mechanisms and the impact on the network is neglected. The main performance indicator used for the evaluation is the load reduction for the VoD server (up to 90%), i.e., its upload traffic savings by utilizing the overlay network [4]. In [22] another approach for peer-assisted VoD is presented. The system includes advanced piece selection and upload allocation techniques especially suitable for a commercial scenario.

Tribler [23] is an open-source P2P VoD streaming platform which is based on BitTorrent, similar to [2] and [3]. In contrast to these, a usable client application exists, which facilitates validation of various extensions in a real prototype. Tribler uses a BitTorrent variant, called give-to-get, that replaces both the chunk selection and the peer selection algorithms to cope with the challenges of video streaming [24]. For the chunk selection, the chunk set after the current playout position is organized into three priority sets, where the high priority set is filled in-order and the subsequent sets according to the rarest-first policy. The work in [25] uses this protocol to demonstrate how to allocate a set of servers efficiently, so that a streaming performance can be guaranteed to users while minimizing the server load.

Applying locality awareness to video streaming works similar to the BitTorrent overlay. The common idea is to prefer local peers over remote peers. This distinction can be applied, for example, when a peer decides which other peers to connect to or from which peers to request certain data. Several works presented locality-aware techniques applicable to (live or on-demand) streaming overlays [26, 27, 28, 29]. Most of them consider the case of live streaming based on application-layer multicast trees and proposes to build subtrees according to the network boundaries, end-to-end delays, or similar metrics [27, 28]. Another approach is presented by Wang et al. where the upload bandwidth is allocated considering (among other parameters) the network topology [26]. While being able to reduce the inter-domain traffic these algorithms cannot improve the streaming quality or reduce server load, thus, missing an incentive for the overlay to apply them.

3. Measurement-based Traffic Management of VoD Overlays

The previous sections revealed that none of the presented approaches has achieved a solution that is acceptable for all three parties: network operators, overlay providers, and users. For example, any strategy for traffic management that explicitly throttles inter-domain traffic results in degradation of the overlay performance. On the other hand, client-side locality awareness brings no benefit to the overlay and, therefore, lacks an incentive to be widely adopted by overlay providers and users. The reason is that the performance of P2P-based content delivery overlays relies on two factors: availability of the content and the upload bandwidth of participating peers. While the overlay performance only considers these factors globally, the network operators should attempt to improve them in the local domain. Only then they can successfully promote locality without hurting overlay performance.

In order to overcome the aforementioned limitations, we propose that network operators provide a clear and measurable *incentive* for locality-aware behavior at the overlay level. To this end, the network operators should promote the selected users compliant with overlay and network requirements by increasing their upload and download bandwidth. This approach is able to increase the overlay performance *and* to reduce the amount of inter-domain traffic resulting in the so-called *triple-win situation*:

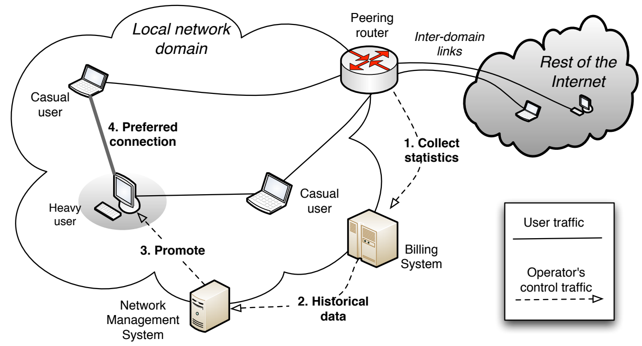


Figure 1: Example of highly active peer promotion from the perspective of a single network operator.

1. Network operators can reduce the costly inter-domain traffic generated by P2P overlays. At the same time they do not risk to disgruntle their clients.
2. Overlay providers benefit from the increased bandwidth of overlay peers. Their own resources are relieved from traffic load even more than without any active traffic management. Thus, the overlay provider can choose either to save server hosting costs, to increase QoS for the delivered content, or even to increase the video resolution.
3. Users can directly and indirectly benefit from incentive-based traffic management by the network operator. The provision of additional resources directly improves the performance of the overlay and, therefore, indirectly the experienced quality of each overlay user. Furthermore, the users selected for promotion can benefit from free resources without extra fees by using network-friendly applications (or application configurations).

A simplified example is shown in Fig. 1. Inside of its domain the network operator monitors the usage profiles of peers to identify those having the highest (potential) impact on the overlay traffic (step 1). The network operator manages this data in its billing and provisioning system that aggregates the historical data and offers it to the network management system (step 2). The network management system analyzes this data, selects best peers and assigns them additional bandwidth, which makes them more attractive for other peers (step 3). Other local peers should detect these promoted peers and download content from them (step 4).

Next, we discuss in detail how single components should be implemented: Monitoring of user traffic, selection of peers to promote, and the actual promotion of peers to HAPs. We also present a mechanism to avoid the (potentially) undesired increase in outbound inter-domain traffic.

3.1. Monitoring Usage Statistics

In order to make the right decisions, the network operator should monitor the parameters listed in Table 1 in regular intervals that has the same duration τ as the promotion interval. An important property of the monitored parameters is the *lack of content-awareness*, which is desired by the network operator (because of the possible copyright infringements) and the overlay provider (because of the possible DRM issues).

This data is gathered in regular intervals and can be collected either by the means of the in-network monitoring (such as NetFlow [30]) or from the overlay, as discussed in [10]. We propose to collect data from the network equipment in the first place. The non-forgeability of this data is its major advantage. Furthermore, this does not require any changes to the monitored overlay applications and, therefore, supports any P2P overlay.

Due to the protocol-independent nature of our approach the network operators are not required to classify the traffic according to a specific P2P protocol (such as BitTorrent, PPLive etc.) but can rely on statistics that contain the total traffic of the given user. Since network operators are able to perform volume-based charging for their users, they have to know their upload and download traffic that can serve as a good indicator to distinguish peer-type from client-type users [31]. Additionally, network operators that already make use of deep packet inspection (DPI) or traffic pattern detection [32] can classify the exchanged data according to the protocol type: P2P, HTTP, etc. (but not necessarily the exact protocol in use). Therefore, in the remainder of this study we assume that the network operator is able to identify P2P users and consider only those P2P users in our evaluations.

Furthermore, network operators have a global view on the locality of Internet addresses that belong to their domain, which allows them to distinguish between local and remote traffic. A real-life example from a network operator monitoring facility is shown in Fig. 2 and visualizes the total upload and download traffic of a single peer. For instance, the active link usage during the morning hours can be attributed to a P2P (file sharing) application.

3.2. Selection of Highly Active Peers

The goal of the selection algorithm is to identify most active and available peers based on the measured data (see Table 1). These peers must be able to act as locality-promoting HAPs and bias the overlay traffic for more locality.

In order to select suitable peers, we consider the following types of relevant user behavior: overlay contribution, seeding ratio, and network-friendliness as discussed below. We define HAP selection metrics that assign a rating value $R(t)$ to each peer p for the currently examined period t so that the network operator can select the highest ranked peers to be promoted.

The *Contribution* metric $C(t)$ represents total contribution of the peer to the overlay. The contribution of the peers is crucial for the overlay performance, since peers who already contributed a lot, could potentially contribute even more. The metric is calculated as:

$$C(t) = \frac{V_{up}(t)}{u(t) \cdot \tau}$$

with $u(t) \neq 0$ and $\tau > 0$ being the duration of the measurement interval. The normalization by $u(t) \cdot \tau$ makes the metric agnostic to the customer's bandwidth and permits a fair comparison between HAPs and normal peers.

The *Network-friendliness* metric $F(t)$ prefers peers that probably apply locality-aware peer selection or that are popular inside the domain, being more quickly discovered by other local peers. We compute $F(t)$ as:

$$F(t) = \begin{cases} \frac{V_{up}^{loc}(t)+V_{down}^{loc}(t)}{V_{up}(t)+V_{down}(t)} & if \quad V_{up}(t) + V_{down}(t) > 0 \\ 0 & otherwise. \end{cases}$$

The *Seeding Ratio* metric $S(t)$ is the amount of a peer's upload traffic relative to the total traffic volume. It enables selecting peers that are altruistic in the sense that they stay online to provide content and not only to consume it (this allows us to avoid the measurement of actual online time of peers, that is practically rather difficult). We calculate $S(t)$ as:[1]

$$S(t) = \begin{cases} S(t) = \frac{V_{up}(t)}{V_{up}(t)+V_{down}(t)} & if \quad V_{up}(t) + V_{down}(t) > 0 \\ 0 & otherwise. \end{cases}$$

Furthermore, we include a *random* HAP selection metric that assigns a random rating value to a peer. It serves as a baseline for comparison since it does not rely on any knowledge about the peers' behavior.

As discussed above, ideally the HAP promotion should consider both network- and overlay-related metrics. The question arises how to combine such metrics. One possible solution is a weighted sum approach as proposed, e.g., in [10, 27]. However, the weighting of such different metrics as presented above is rather difficult. Instead, we propose a hierarchical filtering approach, where one metric is used to remove unsuitable peers and the remaining candidates are ranked by the second metric. Thereby, we

[1] Note that our definition differs from the seeding ratio common in the BitTorrent networks which is defined as $\frac{V_{up}(t)}{V_{down}(t)}$. Our version has the benefit of normalization, since all values will be in the range [0 : 1]. Besides this, the resulting order of peers is the same.

Table 1: Traffic statistics collected per user and measurement interval t.

Parameter	Description
$V_{up}(t)$	Traffic uploaded
$V_{up}^{loc}(t)$	Traffic uploaded within the local domain
$u(t)$	Upload bandwidth during last measurement interval t
$V_{down}(t)$	Traffic downloaded
$V_{up}^{loc}(t)$	Traffic downloaded within the local domain

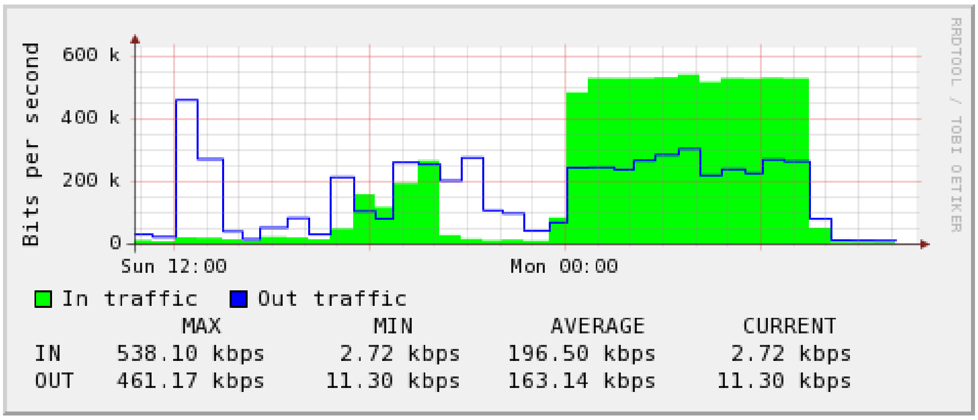


Figure 2: Example of a traffic monitoring of a single user over 24 hours.

use Contribution $C(t)$ as our primary metric and Network-friendliness $F(t)$ as our secondary metric.[2]

Let us consider a set P of candidate peers N and the primary metric C. We define $C_{r_1}(P)$ as the r_1-th percentile of P according to C. In the first filtering step, the best $r_1 \cdot N$ peers are selected as: $P_C = \{p \in P | C(p) \geq C_{r_1}(P)\}$. This allows to remove all peers that do not show significant activity in the overlay. In the second filtering step, the best $r_2 \cdot |P_C|$ peers are selected resulting in the overall number of $r_1 \cdot r_2 \cdot N$ selected peers. Using Network-friendliness as the secondary metric (and its r_2-th percentile) we obtain $P_{C,F} = \{p \in P_C | F(p) \geq F_{r_2}(P_C)\}$. For example, if 20% of peers can be promoted, the operator could set $(r_1, r_2) = (0.5, 0, 4)$.

The HAP selection algorithm must also consider that the behavior of peers and, therefore, the measured values, might fluctuate over time, either due to random and diurnal effects, or because of changes in the behavior of single users. The usage of historical data can alleviate the effect of such fluctuations, but older values should receive lower weights to allow for long-lasting changes in user behavior and in order to keep the entrance barrier low for new peers.

Therefore, we choose the *modified exponential moving average* [33] to aggregate historical data with exponentially diminishing weights. Given a certain selection metric R for the current measurement interval $t \in \mathbb{N}$, this results in the aggregated rating R' with:

$$R'(t) = \begin{cases} \alpha \cdot R(t) + (1-\alpha) \cdot R'(t-1) & for \quad t > 0 \\ 0 & for \quad t = 0. \end{cases}$$

A useful property of this metric is that the network operator has to store only a single historical value per peer, resulting in a reduced storage and computational complexity. The value of α depends on the interval duration τ and the user behavior fluctuations. For our evaluation, we set $\alpha = 0.5$, so that an old value $R(t-x)$ is effectively weighted with $1/2^x$.

3.3. Changing User Access Profile

The proposed incentive-based traffic management technique requires on-the-fly automated updates of the customer access profiles. In our case this is the increase of the totally accessible upload and download bandwidth of certain users. While there are different operator- and vendor-specific solutions possible, we present one real example where our approach was successfully implemented by a network operator[3].

The resulting network architecture is presented in Fig. 3. In this case study, the customer access bandwidth is not limited by a DSLAM but it is throttled by the use of a customized Linux-based traffic shaper. Thereby, the bandwidth provided to single users by the DSLAM is one or two times higher than the shaped bandwidth. Such an architecture that is otherwise used to provide triple-play

[2]in Sect. 5.2 we demonstrate that Contribution outperforms Seeding ratio as a single HAP selection metric.

[3]`http://www.prime-tel.com`

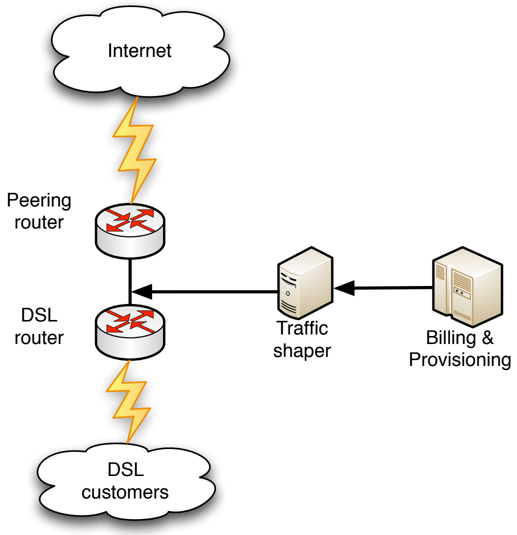


Figure 3: Case study of HAP promotion.

or similar services that require QoS enforcement for different types of traffic, can be easily reused for our approach. Here, the billing and provisioning subsystem stores the current bandwidth assigned to single peers and the traffic shaper enforces these limits. The applied limits are then reconfigured dynamically to promote certain customers to HAPs. This case study demonstrates the feasibility of the proposed approach, where the reconfiguration of clients takes place at least once per day (though it could be also done in the range of few hours).

3.4. Avoiding Outbound Traffic Increase

So far, we considered increasing the users' bandwidth *globally*, i.e., that the network operator cannot control how clients use the additional bandwidth. Indeed, peers promoted to HAPs might upload a lot of traffic to remote peers and even increase the outbound inter-domain traffic. Even if such peers might be demoted after the next HAP selection round, the new set of peers might exhibit the same behavior. The reasons for such network-unfriendly behavior might be diverse, including the lack of locality awareness in the overlay or a deficit of available bandwidth (or desired content) in other network domains. As a consequence, promotion of peers might lead to an undesired increase of the outbound traffic.

To avoid this, we propose that the network operator increases the bandwidth only *locally*, that is, inside of its network domain. This is an alternative to the *global* bandwidth increase that we consider as the default option. This decision may have a significant impact on the overall performance of the HAP promotion approach. A local bandwidth increase is more efficient from the network operator's perspective if outbound traffic is costly for the given operator. In the scenario presented in Sect. 3.3, the local bandwidth increase can be enforced by the traffic shaper by matching the receivers IP address with the local IP prefixes.

4. Evaluation of the Single Swarm Case

The goal of this study is to assess whether the involved stakeholders can benefit from the HAP promotion in a realistic environment. For this purpose we use an instrumented client on the basis of the Tribler VoD client [11]. We perform the measurements in the German Lab testbed[4] and apply a real-time user promotion. This section covers the results of the following experiments: (1) *Impact of adoption by all network operators*, which compares the impact of locality awareness and HAP promotion on users, overlay providers, and network operators; (2) *Impact on an early adopter*, which is the case when only a single network operator deploys HAP promotion.

4.1. Methodology

The scenario for our experiments is shown in Table 2. Due to the restrictions of the testbed environments, we limit the experiments both in terms of the overlay size and the number of considered parameter variations. These restrictions are dropped in the subsequent simulation study (see Sect. 5). Our setup comprises four network domains: three customer domains containing peers and one server domain. The overlay peers are equally distributed among the network domains and, if locality awareness is in place, only 50% of peers make use of it. Every testbed configuration is repeated three times and we present average values and standard deviations.

We capture the following metrics to understand the impact of the mechanisms under study: *traffic uploaded by servers* to capture the costs for the overlay provider (and implicitly for the overlay users) and *inter-domain traffic* to capture network operators' costs. For the latter metric we also distinguish between the *inbound and outbound inter-domain traffic* since they might have different impact on costs for certain operators. Content providers are represented using a prototype implementation of adaptive servers [25]. Those servers reside in a separate domain and data exchange between peers and servers counts as inter-domain traffic. We further capture the total playback delays of individual users.

4.1.1. Locality-aware Peer Selection

We integrated the locality-aware peer selection mechanisms into the Tribler client with the primary focus on flexibility. Our instrumented client uses a client-side variation of Biased Neighbor Selection (BNS) [6] and Biased Unchoking (BU) as described in [8]. Upon connection establishment, e.g., when the peer discovers new potential

[4] http://www.german-lab.de/

Table 2: Setup of single swarm experiments.

Parameter	*Values* (**default**, variations)
Experiment duration	90 min.
Videos	length = 15 min., bitrate = 540 kbps
Topology	3 customer domains and 1 server domain
Available servers	0-10 (adaptive)
Server bandwidth (upload)	2048 kbps
Peer bandwidth (down, up)	2048/kbps, 512 kbps
Peer arrival rate	Exponentially distributed with 8 peers/min.
Peers' online time	75% selfish and 25% altruistic
- Selfish	$t_{\text{online}} = t_{\text{video}} \cdot z,\, z = \mathcal{U}(0,1)$ (uniform)
- Altruistic	$t_{\text{online}} = t_{\text{video}} + z,\, z = \exp\left(\frac{1}{\text{video length}/2}\right)$
Locality awareness	**none**, 50% of peers
- BNS filtering	90% local connections
Adoption of HAP promotion	**none**, all, single operator
- Peer promotion interval	5 min.
- Ratio of promoted peers	20% per domain
- Additional bandwidth per HAP	100%

neighbors via the tracker response, peer selection according to BNS takes place. Thus, a peer connects preferentially to peers located within the same network domain. Upon upload allocation, when a peer selects a neighbor for the optimistic unchoke, peer selection according to BU takes place. Here, a peer tries to unchoke a random *local* peer.

Both strategies use an internal peer selection API that ranks candidate peers based on various sources. These sources can be *internal* knowledge databases such as preloaded GeoIP databases[5] or *external* knowledge databases such as an ALTO compliant service [5]. Peer ratings from external knowledge databases are cached for a configurable amount of time in order to reduce communication overhead and to avoid additional delays during connection establishment and unchoking. This architecture allows easy adoption of new knowledge databases. It further facilitates the usage of the implementation in various environments, such as testbed experiments or real-world deployments.

4.1.2. HAP Promotion

Network operators deploy HAP promotion in order to identify beneficial peers according to the combined HAP selection metric (see Sect. 3.2) and modify their upstream capacities. Due to the restrictions of the underlying testbed, we cannot implement HAP promotion at the network level by e.g. using the tc suite.[6] Instead, we emulate the rate limitation on the client-side. First, the upstream bandwidth of each client is set to a predefined access profile according to testbed parameters. During runtime operators collect bandwidth utilization reports from instrumented clients and instruct selected clients to update their internal rate limits according to their current promotion status.

4.2. Impact of HAP Promotion by all Operators

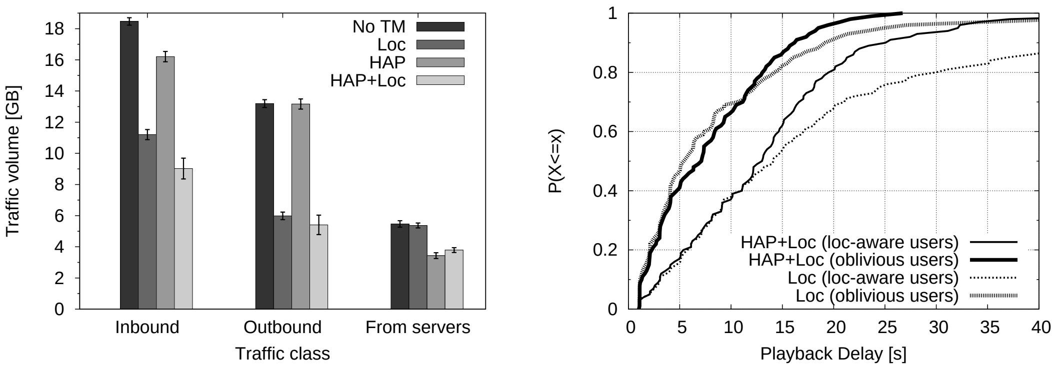
In order to measure the impact of our approach, four different combinations of traffic management approaches are considered: (1) no traffic management (*No TM*), (2) locality-aware peer selection without HAP promotion (*Loc*), (3) all network operators apply HAP promotion but peers do not behave locality-aware (*HAP*), and (4) combination of HAP promotion and locality awareness (*HAP+Loc*).

Fig. 4 presents the outcome of HAP promotion applied by all operators for the involved stakeholders (users, overlay provider, and network operators). We observe (Fig. 4a) that locality-aware peer selection achieves a large reduction of inter-domain traffic (40% of inbound and 55% of outbound traffic). This reduction goes even further if we combine locality awareness with HAP promotion. As expected, the *No TM* case shows the largest amount of server traffic and locality-aware peer selection does not reduce this server traffic significantly (Fig. 4a). On the other hand, HAP promotion (with or without locality awareness) results in server traffic reduction by 36–38%.

Additionally, Fig. 4b shows the performance of locality-aware and oblivious users in two different scenarios. We observe that locality awareness decreases streaming performance in terms of total delay. In contrast, HAP promotion increases the streaming performance and can compensate for negative effects that are introduced by using locality-aware peer selection. The graph also shows that there is almost no difference between the performance of oblivious users in both scenarios. We further observe that mostly locality-aware peers benefit from local HAPs.

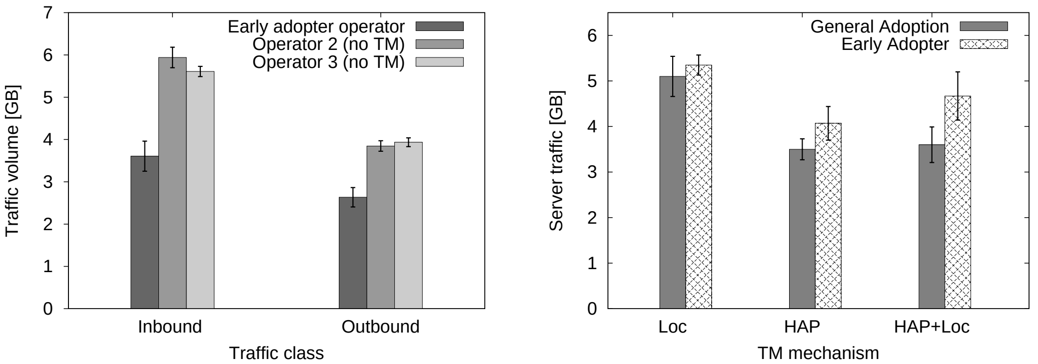
Furthermore, our measurement data reveals that within promoted peers there were four times more locality-aware

[5] `http://www.maxmind.com/app/ip-location`
[6] `http://www.linux.org/docs/ldp/howto/Traffic-Control-HOWTO/intro.html`



(a) Inter-domain and server traffic. (b) Performance of locality-aware and oblivious users.

Figure 4: Single swarm scenario: impact of HAP promotion by all operators.



(a) Inter-domain traffic (HAP+Loc). (b) Server traffic.

Figure 5: Single swarm scenario: Impact of HAP promotion by a single operator (early adopter).

than oblivious peers, which means that locality-aware peers are rewarded in terms of additional free bandwidth. This provides an incentive to be network-friendly even if the performance might be slightly degraded compared to the oblivious peers. To conclude this experiment, we can observe that in cases when all network operators apply HAP promotion the combination with locality awareness achieves the best situation for the overlay provider and the network operators.

4.3. Impact of Adoption by a Single Operator

In this experiment we consider the case when only a single operator applies HAP promotion. In this regard, only peers inside of its network domain can be promoted to HAPs and only peers inside of its domain apply locality-aware peer selection. Out of those peers, 20% can be promoted to HAPs and 50% behave locality-aware.

The outcome of this scenario is shown in Fig. 5. Even with only 50% of peers behaving locality-aware, the early adopter clearly benefits from the combination of HAP promotion and locality awareness. As Fig. 5a shows, both the inbound and outbound traffic of operator 1 are roughly 40% lower than for the other operators (despite the same amount of peers per network domain). Furthermore, regarding the server traffic we observe that with HAP promotion applied only by operator 1 the server traffic decreases (cf. Fig. 5b), though not at the same extent as when all operators deploy HAP promotion.

We also compared the streaming performance for users belonging to the early adopter and other operators but observed no significant difference. Regarding the users, we observed negligible deviations between different operators regarding the streaming experience. At the same time, mostly locality-aware peers benefit from HAP promotion by receiving additional bandwidth (more than 80% of promoted peers are locality-aware).

5. Evaluation of the Multi Swarm Case

The previous section demonstrated the effect of HAP promotion with a real application in a testbed environment. However, due to the limitations of the testbed, we did not study the effect of longer promotion intervals (at least few hours) that can be realized in today's networks (see Sect. 3.3). Therefore, in this section we apply simulations as a means to assess the impact of such promotion

Table 3: Setup for experiments with multiple swarms.

Parameter	*Values* (**default**, variations)
Peers	50,000
- Initial upload bandwidth	700 kbps
- Cache size	4 GB
- Seeding behavior	50%: 0 hours and 50%: 1 hour
- Inter-request time	20%: 8 hours and 80%: 48 hours
- Peer selection policy	**locality-aware**, oblivious, mixed
Videos	2,500
- Size	800 MB
- Rate	950 kbps
- Popularity distribution	Zipf ($\alpha = 0.85$)
Network Operators	10 customer and 1 server domain
- Size distribution	32, 17, 13, 12, 12, 4, 3, 3, 1, 1%
HAP promotion	25% of peers each 24 hours
- HAP selection metric	**contribution**, network-friendliness, seeding ratio, random
- Total additional bandwidth	**100%**, 0 – 300%
- Bandwidth increase	**global**, local
Alternative mechanisms	no TM, blocking, P2P caches

intervals with large amount of users participating in multiple swarms. We analyze the impact of different parameters of our approach and compare HAP promotion with other traffic management approaches.

5.1. Methodology

Our simulation scenario models the behavior of a commercial peer-assisted VoD overlay that spans the domains of several network operators. An efficient implementation of this system in a custom discrete event-based simulator allows us to simulate a scenario of four weeks.

Table 3 shows the simulation setup (with default values shown in bold). The peers are spread over ten heterogeneous network domains following the distribution of German users collected by Ookla [34]. We further model a separate domain for the overlay provider, which contains only the content servers. The domains are organized in a star topology, which is sufficient to capture the inter- and intra-domain traffic of single operators.

We model the user behavior based on various measurement studies revealing heterogeneous usage patterns [35, 36, 37, 31]. For this purpose, we divide the users into four groups based on two independent properties: seeding behavior and inter-request time. For the inter-request time, we apply the Pareto distribution to user requests, resulting in 20% *heavy users* generating 80% of the streaming requests (similar to the patterns observed by Cho [31] and Basher [38]). Since the seeding time describes the level of altruism, we divide the users in *selfish* users, that don't seed at all, and *altruistic* users, whose seeding times are exponentially distributed with the mean of one hour. The content is modeled with 2,500 videos where each video has an average bitrate of 950 kbps. We model the content popularity by letting users choose videos to watch according to a Zipf distribution (with Zipf parameter $\alpha = 0.85$) [39].

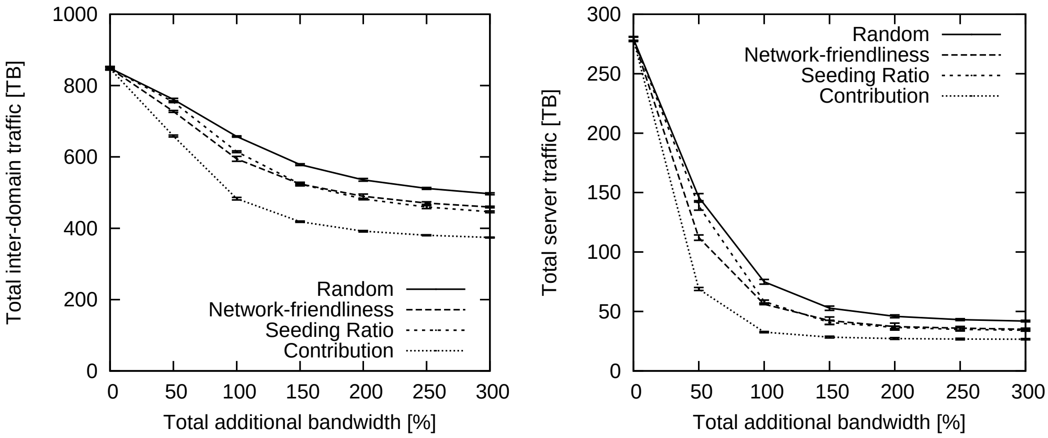
The simulation model also includes all relevant mechanisms of HAP promotion (monitoring, selection, and bandwidth update). By default, the increased bandwidth is not restricted to the local domain (i.e., *global increase*). The promotion interval is set to one day and 25% of peers are promoted by default. Independent of the HAP promotion, peers can behave either *network-oblivious* or *locality-aware* when choosing their communication partners. In mixed scenarios, only a certain percentage of peers behave locality-aware. Since servers are considered as most costly from the overlay perspective, both peer selection policies prefer remote peers over content servers when choosing download sources.

While HAP promotion and locality awareness at the overlay level are the main traffic management (TM) techniques analyzed in this paper, we also consider two alternative mechanisms available to network operators as a baseline for comparison: *blocking* of inter-domain P2P traffic and *deployment of P2P caches* that act as superpeers but serve only local peers.

We capture the same metrics as in the single swarm experiments (see Sect. 4.1) with the exception of the playback delays since in the simulation model the servers assure that the required video data is supplied in time. We further focus on the total inter-domain traffic that is the sum of inbound and outbound traffic.

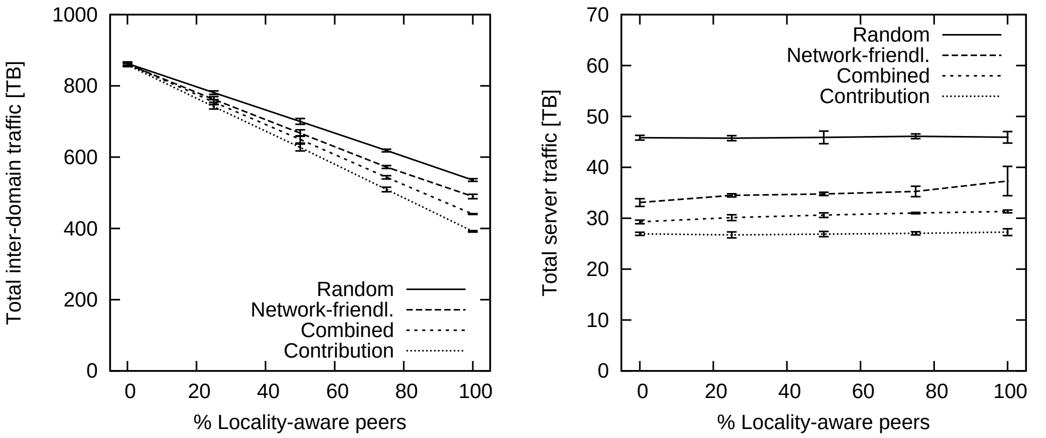
5.2. General Impact of HAP Promotion

This scenario contains heavy users and casual users who can be either altruistic or selfish. However, we assume



(a) Inter-domain traffic. (b) Server traffic.

Figure 6: Impact of single HAP selection metrics.



(a) Inter-domain traffic. (b) Server traffic.

Figure 7: Combined vs. single HAP selection metrics.

that all peers behave locality-aware. This assumption is dropped in the subsequent experiment.

Fig. 6 demonstrate the impact of the total bandwidth assigned for HAP promotion and its interplay with HAP selection metrics in use. Even with the *random* HAP selection metric the inter-domain traffic can be significantly reduced by up to 40% (see Fig. 6a). At the same time the server traffic can be reduced from 280 to 45 TB (reduction of 85%), which results in the intended *win-win* situation (see Fig. 6b). Besides the random selection metric the other metrics perform even better, resulting in higher benefits both for the overlay and network. The *contribution* metric turns out to be the best HAP selection metric in all setups, reducing the inter-domain traffic by up to 55% and server traffic by up to 90%. If we consider the operators to invest only 100% of additional upload bandwidth, the improvement is still significant, with 43% inter-domain traffic reduction and 88% server traffic savings with the best metric. This increase of the total upload bandwidth by 100% is considered as our *working point* for the next experiments.

In order to understand the reason that the contribution metric outperformed the other metrics, Fig. 8 presents the percentage of promoted peers within single behavioral groups (for a single simulation run). We observe that the HAP selection based on peers' contribution prefers heavy users over casual, but also prefers altruistic behavior in the second place. These users are frequently online and are able to serve more requests from other users, and, even more, they request more content and, therefore, can serve most popular content. For comparison, the seeding ratio metric prefers altruistic users that stay longer online to serve other users, but their request frequency is often lower than that of heavy users.

5.3. Incentives for Locality Awareness

In the previous experiment we saw that if 100% of peers behave locality-aware, then the contribution metric provides the highest benefit both for network operators and

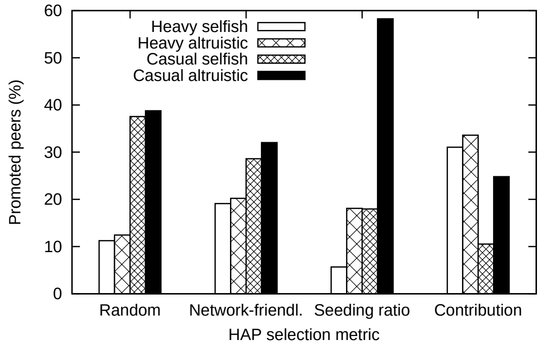


Figure 8: Type of users promoted by single HAP selection metrics.

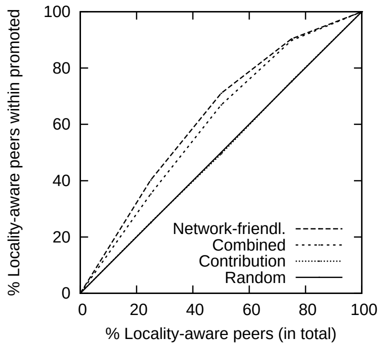
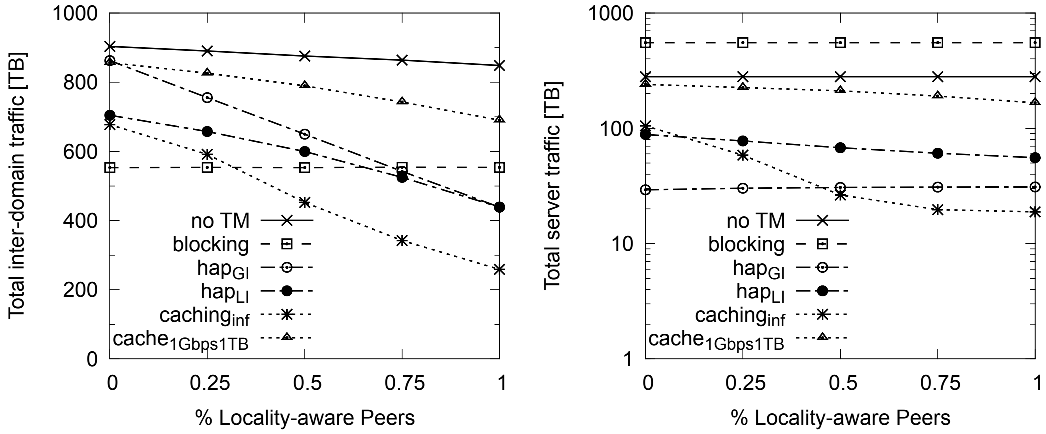


Figure 9: Locality-aware peers within promoted peers.



(a) Inter-domain traffic.

(b) Server traffic (logarithmic scale).

Figure 10: Local vs. global bandwidth increase.

the overlay provider. In this experiment, we drop the assumption of a fully locality-aware overlay and vary the percentage of locality-aware peers between 0% and 100%.

We study the effect of the network-friendliness metric and its combination with the contribution metric (see Fig. 7). When the percentage of locality-aware peers is equal to zero, all metrics perform the same, while the increasing locality awareness degree amplifies the effect of HAP promotion. Furthermore, the contribution metric again outperforms other metrics and the random selection performs worst. Finally, the combination of the contribution and network-friendliness metrics offers a trade-off between pure contribution and pure network-friendliness, both for the overlay and the network (cf. Fig. 7a). We further consider the impact of HAP selection metrics on the server traffic and observe that the combined metric provides a reduction comparable to the contribution metric, thus outperforming the random selection and pure network-friendliness (see Fig. 7b).

In order to understand the impact on users, we plot the percentage of promoted *locality-aware* peers as a function of their total percentage in the overlay. (Fig. 9). We observe that with both selection metrics based on the network-friendliness, the probability to be promoted is higher for *locality-aware users* because their percentage in the promoted peers is higher than their percentage in the overlay population. Thus, users have a clear benefit to behave locality-aware, which in turns results in a higher benefit for the network operators.

5.4. Alternative Solutions and the Effect of Local Bandwidth Increase

In this experiment we compare HAP promotion with alternative mechanisms to traffic management (TM). Fig. 10 shows the performance of blocking, P2P caches, HAP promotion (with global or local bandwidth increase), and no traffic management at all. While each of this mechanisms can be applied by network operators, we also analyze the impact of different locality awareness degrees at the overlay level. Without HAP promotion (the *no TM* curve), we observe only a minor benefit of locality-aware peers for operators and no impact on the server traffic. If network operators apply blocking of inter-domain P2P connections, the inter-domain traffic can be reduced by 35%. However, this savings for the network operators come at the cost of server traffic increasing by a factor of two. Therefore, this approach does not achieve the desired win-win situation. On the other hand, P2P caches and HAP promotion show the desired behavior regarding the impact of higher locality awareness at the overlay level. The lowest inter-domain traffic is achieved with a high degree of locality-awareness. Furthermore, HAP promotion with local bandwidth increase (as proposed in Sect. 3.4) reduces the server traffic by 38% providing a clear incentive for the overlay to behave locality-aware, which in turn benefits the network operators (cf. Fig. 10a). We conclude that both P2P caches and HAP promotion result in the desired win-win situation, while the latter approach avoids the legal issues and is protocol-independent. To show the potential of P2P caches we plot both caches with infinite resources ($cache_{inf}$) and with realistic upload bandwidth of one gigabit per second and one terabyte storage space ($cache_{1Gbps1TB}$). In addition, a P2P cache serves all local peers and does consequently not provide an incentive for the users to act according to the operator's policies.

6. Summary and Conclusions

This paper presented a cooperative approach to traffic management of P2P-based streaming overlays, called highly active peer (HAP) promotion. Instead of unilateral approaches such as traffic shaping or overlay-side locality awareness, all stakeholders contribute to obtain mutual benefit. The overlay peers behave locality-aware by exchanging data preferentially with local peers, while the network operators promote selected users in terms of their access bandwidth. This creates an incentive for the overlay (both the overlay provider and users) to employ locality-aware mechanisms. In addition, the network operators are able to decrease the inter-domain traffic.

To show the feasibility, we presented a proof-of-concept study performed by a real network operator with real customers. This comprises in particular the measurement of the traffic exchanged by individual users and the ability to modify users' access profiles dynamically. We proposed different metrics for network operators to select peers to be promoted to HAPs and investigated their performance.

To this end, we evaluated our approach in a testbed and through large scale simulations. Our analysis showed that inter-domain traffic and the load on servers of the content providers can be reduced significantly. Furthermore, locality-aware end-users receive the benefit of additional "free" bandwidth and, contrary to pure locality awareness, observe almost no penalty in terms of streaming performance. We also considered the HAP promotion by only a single operator and demonstrated that even in that case this operator benefits. This shows that HAP promotion can be applied successfully even if only some network operators support it. Finally, we compared HAP promotion with different approaches to overlay traffic management and observed our approach performing similar to the best alternative (P2P caches with high capacity). However, it lacks the associated content-awareness as well as protocol-dependence and provides incentives for users and overlay providers to behave locality-aware at the same time.

[1] Cisco visual networking index: Forecast and methodology, 2009–2014 (2010).
URL http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360.pdf

[2] C. Dana, D. Li, D. Harrison, C. N. Chuah, Bass: Bittorrent assisted streaming system for video-on-demand, in: IEEE Workshop on Multimedia Signal Processing, 2005.

[3] A. Vlavianos, M. Iliofotou, M. Faloutsos, Bitos: Enhancing bittorrent for supporting streaming applications, in: IEEE INFOCOM, 2006, pp. 1–6.

[4] Y. R. Choe, D. L. Schuff, J. M. Dyaberi, V. S. Pai, Improving vod server efficiency with bittorrent, in: ACM MULTIMEDIA '07, 2007, pp. 117–126.

[5] Charter of the IETF Working Group on Application-Layer Traffic Optimization (ALTO), http://www.ietf.org/html.charters/alto-charter.html (2011).

[6] R. Bindal, P. Cao, W. Chan, Improving Traffic Locality in BitTorrent via Biased Neighbor Selection, in: International Conference on Distributed Computing Systems (ICDCS), 2006.

[7] V. Aggarwal, A. Feldmann, C. Scheideler, Can ISPS and P2P Users Cooperate for Improved Performance?, ACM SIGCOMM Computer Communication Review 37 (2007) 29–40.

[8] S. Oechsner, F. Lehrieder, T. Hoßfeld, F. Metzger, K. Pussep, D. Staehle, Pushing the performance of biased neighbor selection through biased unchoking, in: IEEE International Conference on Peer-to-Peer Computing (IEEE P2P), 2009.

[9] F. Lehrieder, S. Oechsner, T. Hoßfeld, D. Staehle, Z. Despotovic, W. Kellerer, M. Michel, Mitigating Unfairness in Locality-Aware Peer-to-Peer Networks, International Journal of Network Management (IJNM), Special Issue on Economic Traffic Management 21 (1) (2011) 3–20.

[10] K. Pussep, S. Kuleshov, C. Groß, S. Soursos, An incentive-based approach to traffic management for peer-to-peer overlays, in: Workshop on Economic Traffic Management (ETM), 2010.

[11] Tribler Client. [link].
URL http://tribler.org/

[12] P. Eckersley, F. von Lohmann, S. Schoen, Packet Forgery By ISPs: A Report On The Comcast Affair, https://www.eff.org/files/eff_comcast_report.pdf (November 2007).

[13] F. Lehrieder, G. Dán, T. Hoßfeld, S. Oechsner, V. Singeorzan, The Impact of Caching on BitTorrent-like Peer-to-peer Systems, in: IEEE International Conference on Peer-to-Peer Computing (IEEE P2P), 2010.

[14] T. Karagiannis, P. Rodriguez, K. Papagiannaki, Should internet service providers fear peer-assisted content distribution?, in: ACM Internet Measurement Conference (IMC'05), 2005.

[15] R. Cuevas, N. Laoutaris, X. Yang, G. Siganos, P. Rodriguez, Deep diving into bittorrent locality, in: INFOCOM, IEEE, 2010.

[16] H. Xie, Y. R. Yang, A. Krishnamurthy, Y. G. Liu, A. Silberschatz, P4P: Explicit Communications for Cooperative Control Between P2P and Network Providers, in: ACM SIGCOMM, 2008.

[17] D. R. Choffnes, F. E. Bustamante, Taming the torrent: a practical approach to reducing cross-ISP traffic in Peer-to-Peer systems, SIGCOMM Computer Communication Review 38 (4) (2008) 363–374.

[18] P. Racz, S. Oechsner, F. Lehrieder, BGP-based Locality Promotion for P2P Applications, in: International Conference on Computer Communication Networks (ICCCN), 2010.

[19] S. Le Blond, A. Legout, W. Dabbous, Pushing BitTorrent locality to the limit, Computer Networks 55 (3) (2010) 541–557.

[20] M. Piatek, H. V. Madhyastha, J. P. John, A. Krishnamurthy, T. Anderson, Pitfalls for ISP-friendly P2P design, in: Workshop on Hot Topics in Networks (HotNets), 2009.

[21] C. Huang, J. Li, K. W. Ross, Peer-Assisted VoD: Making Internet Video Distribution Cheap, in: International Peer to Peer Symposium (IPTPS), 2007.
[22] O. Abboud, K. Pussep, M. Mueller, A. Kovacevic, R. Steinmetz, Advanced Prefetching and Upload Strategies for P2P Video-on-Demand, in: Workshop on Advanced video streaming techniques for peer-to-peer networks and social networking, 2010.
[23] J. Pouwelse, P. Garbacki, J. Wang, A. Bakker, J. Yang, A. Iosup, D. Epema, M. Reinders, M. van Steen, H. Sips, Tribler: A social-based peer-to-peer system, Concurrency and Computation: Practice and Experience 20 (2008) 127–138.
[24] J. D. Mol, J. Pouwelse, M. Meulpolder, D. Epema, H. Sips, Give-to-Get: An Algorithm for P2P Video-on-Demand, in: Multimedia Computing and Networking (MMCN), 2008.
[25] K. Pussep, O. Abboud, F. Gerlach, R. Steinmetz, T. Strufe, Adaptive Server Allocation for Peer-assisted VoD, in: IEEE International Parallel and Distributed Processing Symposium (IPDPS), 2010.
[26] J. Wang, C. Huang, J. Li, On ISP-friendly Rate Allocation for Peer-assisted VoD, in: ACM International Conference on Multimedia (ACM Multimedia), 2008.
[27] J. Seedorf, S. Niccolini, M. Stiemerling, E. Ferranti, R. Winter, Quantifying Operational Cost-Savings through ALTO-Guidance for P2P Live Streaming, in: Workshop on Economic Traffic Management (ETM), 2010.
[28] F. Picconi, L. Massoulie, ISP-friend or Foe? Making P2P Live Streaming ISP-aware, in: International Conference on Distributed Computing Systems (ICDCS), 2009.
[29] K. Kerpez, Y. Luo, F. J. Effenberger, Bandwidth Reduction via Localized Peer-to-Peer (P2P) Video, International Journal of Digital Multimedia Broadcasting 2010 (2010) 1–11.
[30] R. Sommer, A. Feldmann, NetFlow: Information Loss or Win?, in: ACM SIGCOMM Workshop on Internet Measurement (IMW), 2002.
[31] K. Cho, K. Fukuda, H. Esaki, A. Kato, Observing Slow Crustal Movement in Residential User Traffic, in: ACM International Conference on emerging Networking EXperiments and Technologies (CoNEXT), 2008.
[32] T. Karagiannis, K. Papagiannaki, M. Faloutsos, BLINC: Multilevel Traffic Classification in the Dark, in: ACM SIGCOMM, 2005.
[33] J. Prins, e-Handbook of Statistical Methods, in: C. Croarkin, P. Tobias (Eds.), 6.3.2.4. EWMA Control Charts, NIST/SEMATECH, 2010.
URL `http://www.itl.nist.gov/div898/handbook/pmc/section3/pmc324.htm`
[34] Ookla, Net Index.
URL `http://www.netindex.com/`
[35] B. Cheng, L. Stein, H. Jin, Z. Zhang, Towards Cinematic Internet Video-on-Demand, in: ACM European Conference on Computer Systems 2008 (EuroSys), 2008.
[36] Y. Huang, T. Z. Fu, D.-M. Chiu, C. Huang, J. C. Lui, Challenges, design and analysis of a large-scale p2p-vod system, in: ACM SIGCOMM, 2008.
[37] C. Huang, A. Wang, J. Li, K. W. Ross, Understanding Hybrid CDN-P2P: Why Limelight Needs its Own Red Swoosh, in: ACM International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV), 2008.
[38] N. Basher, A. Mahanti, A. Mahanti, C. Williamson, M. Arlitt, A Comparative Analysis of Web and Peer-to-Peer Traffic, in: ACM International Conference on World Wide Web (WWW), 2008.
[39] F. T. Johnsen, T. Hafsoe, C. Griwodz, P. Halvorsen, Workload Characterization for News-on-Demand Streaming Services, in: IEEE International Performance, Computing, and Communications Conference (IPCCC), 2007.