Maximizing video quality for several unicast streams in a multipath overlay network

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***Abstract*—A streaming system that uses an overlay network for multipath streaming needs to make decisions concerning the distribution of the available bandwidth among all of its clients. This decision making should aim at delivering the best possible quality to all clients while providing an optimal utilization of the network resources. We consider a scenario where most requests are negligibly overlapped in time. It implies that using multicast is not efficient, and instead, the streams are striped and allocated to multiple paths from the sever to the client.**

To evaluate how well the rate-allocation algorithms approach optimality, we have earlier built a benchmarking system that provides the optimal solution for assigning available bandwidth to delivery paths. However, as video is not linearly related to bitrate, the trivial maximization of the total consumed bandwidth does not necessary maximize the video quality. To address this problem, we define a metric that assesses a video quality for a group of clients that we use as a utility function in the revised benchmarking system. Due to its concavity, this utility function also distributes the bandwidth resources proportionally fair between the clients of the system.

I. INTRODUCTION

This paper examines the performance of overlay multipath streaming for the delivery of video-on-demand in the Internet in terms of the video quality of several clients. A typical usage of the proposed approach is an efficient rate allocation for multimedia streaming services provided by content delivery networks (CDN). CDNs are often used for data caching and request routing, and, so far, have not been exploited for multipath routing.

We consider a multisource system, meaning that several senders offer multimedia content for streaming. A representative scenario is described by a system illustrated in Figure 1. The system consists of multiple service providers forwarding their content via Internet to multiple users. To be able to deploy multipath streaming in the application level the streaming is built upon a system of overlay nodes. The nodes of this overlay network are able to connect directly to each other using the Internet, forming a *fully meshed* overlay network. The service providers and clients are connected to the overlay network. In order to make optimal routing decisions, the system needs to perform estimations of available bandwidth along the paths between the overlay nodes. Such a scenario can typically represent a content delivery network with servers used both for caching and multipath routing of the video content.

Our scenario considers a situation where most requests are negligibly overlapped in time. These conditions imply that multicast does not save any bandwidth and that streams can be delivered by unicast instead. We do not consider multipath streaming that makes use of network coding [1] or caching.

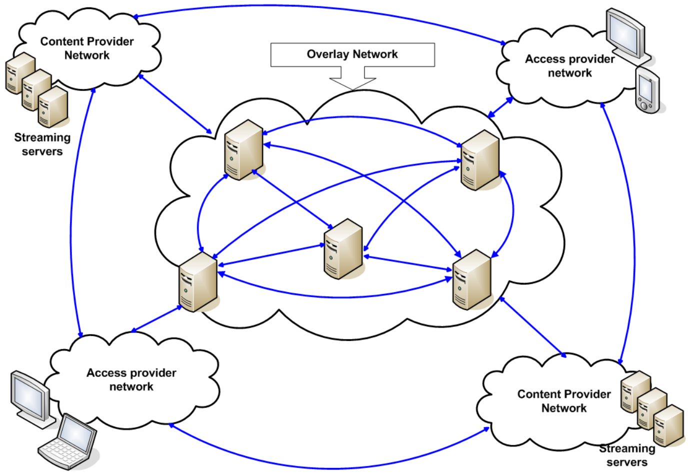

Figure 1. Scenario example

The advantage of using an overlay network for multisource multipath streaming under these conditions is that streams can be split up and re-routed to improve the total amount of bandwidth that is available for streaming from the servers to every single client, even when individual overlay links have insufficient bandwidth. Clients that do not suffer from bottlenecks in the access network are likely to compete for the bandwidth on at least some overlay links.

We build on our previous work [2] that studies a benchmarking system for multipath overlay networks. This benchmarking system provides us with the best possible distribution of the streams over multiple delivery paths in terms of available bandwidth. In the paper, we consider usage of different utility functions that can capture video quality and provide us with more fair distribution of the network resources.

The rest of the paper is organized as follows. After discussion of existing overlay streaming systems in Section II, we present well-known definitions of fairness in Section III that are applied to bandwidth sharing. We define a utility function to express quality of multiple videos in Section IV. The mathematical model of the benchmarks is discussed in

Section V. We analyze and compare results of the linear and logarithmic benchmarks in Section VI, before concluding in Section VII.

II. RELATED WORK

To improve the quality of multimedia streams delivered to clients over the shared Internet infrastructure, algorithms have been proposed that exploit multipath delivery by splitting streams between different paths [3], [4].

Several works studied multipath solutions specifically addressing the problem of multipath streaming in the application level by using overlay or peer-to-peer infrastructure [5]–[8]. Though these solutions mostly focus on peer management in the overlay network and on peer selection for constructing the best possible topologies, some of these works also consider how the streaming rates should be allocated to multiple paths.

SplitStream [6] is built upon an overlay network called cooperative environments and is used for multicast and content distribution. In SplitStream, multiple trees are built and used for streaming in order to balance the forwarding load. The peers are organized in trees in a way that each peer serves as an internal node in one tree and as a leaf node in other trees. This principle guarantees that the failure of one node will affect only one tree. The content is split equally into several stripes, which are then multicast using separate trees.

Outreach [7] is another topology construction algorithm that is intended to optimize the peer-to-peer overlay construction. It maximizes the utilization of the peers' available upload bandwidth in order to minimize the bandwidth requirements on the streaming server.

Hefeeda et al. [5] introduce a topology-aware peer-to-peer streaming system. The candidate peers are selected based on proposed in the paper the "goodness" metric. The metric is calculated by using the packet loss and the available bandwidth between the peer and the client. The system is client-based meaning that all decisions about peer selection are made at the client side and the interplay in decision making between different clients is not considered. The selfishness of the clients may lead to the situation where the clients that start the peer selection earlier consume the whole bandwidth.

A simple TCP-based multipath streaming algorithm has been proposed by Wang et al. [9]. The authors assume that there exists a multipath streaming architecture. The server opens several TCP connections, one for each path, and stripes video content over these connections. However, the authors do not consider how the multipath infrastructure is built, and they do not study possible trade-offs between multiple streams.

III. FAIRNESS STRATEGIES

Fairness is an important issue when analyzing and assessing resource allocation algorithms, such as rate control algorithms for multiple clients. Several authors have studied this problem and defined quantitative measures of fairness [10]–[13]. In these studies, fairness applies to allocating rates to different flows, which for the unicast case, can be identified as streams.

Jain et al. [10] defined the quantitative measure of the fairness of a resource allocation as the fairness index given in Eq. 1.

$$\text{fairness index} = \frac{(\sum x_i)^2}{n \cdot \sum x_i^2} \tag{1}$$

This fairness index is applicable to any system with shared resources, independent of any particular application.

Max-min fair resource sharing, as defined by Bertsekas and Gallager [11], allocates the bandwidth to lower-bandwidth streams as requested, while higher-bandwidth streams share the remaining resources equally. This definition gives an absolute priority to lower-bandwidth streams, and can be formulated as follows: A feasible vector of rates $x = (x_s, s \in S)$ is max-min fair if for any other feasible vector $y = (y_s, s \in S)$, the following condition is true:

$$\forall i \in S, j \in S, i \neq j, y_i > x_i : y_j < x_j, x_j \leq x_i \tag{2}$$

If applicable to large-scale system with several possible bottlenecks, this criterion can result in lower total throughput than can be achieved by the system.

As an alternative to min-max fairness, Kelly et al. [12], [13] proposed proportional fairness that favors lower-bandwidth streams less. This criterion is defined as follows: A vector of rates $x = (x_s, s \in S)$ is *proportionally fair* if it is feasible according to Eq. 2, and if for any other feasible vector x^*, the following condition is met:

$$\sum_{s \in S} \frac{x_s^* - x_s}{x_s} \leq 0 \tag{3}$$

This criterion can be implemented in large-scale networks with several bottlenecks that congest the system. As considered in scenario in Section I, several overlay links can suffer from congestion and, therefore, we choose to base our work on this criterion.

IV. UTILITY FUNCTION OF MULTIPLE VIDEOS

To evaluate how good multipath streaming strategies are in terms of optimal bandwidth utilization, we proposed a benchmarking system that provided us with the optimal solution for allocating the bandwidth to the available delivery paths [2]. This benchmark maximizes the total bandwidth assigned to *all* the clients of the system, and solved the optimization problem which we shall explain later in Section V.

In this paper, we expand this benchmark. Instead of tuning the benchmark for the total bandwidth of streams delivered to individual clients, we aim at maximizing video quality for *all* the clients that receive videos from the system at the same time, where we account for heterogeneity of receivers.

For this, we require an understanding of video quality experienced by a group of clients. We realize that the estimation of perceived video quality is an open research field. Video quality experts agree that existing quality estimation methods must be used carefully [14]. For the goals of this paper, however, we make use of a very simple theoretical framework for end-to-end video quality prediction that was presented by Koumaras et al. [15]. One of the presented models operates at the pre-encoding stage, and predicts the video quality of the encoded signal. The authors concluded that the dependency between a bit rate x and the perceived quality of service $\text{PQoS}_{\text{SSIM}}$ can be described by Eq. 4.

$$\text{PQoS}_{\text{SSIM}} = 0.1033 \ln(x) + 0.2940 \tag{4}$$

This function is convenient for our investigation since the dependency is expressed by a function that is concave for all non-zero bandwidths. We intend to use this function for constructing an additive utility function that expresses the video quality for a group of clients. The region of feasible solutions is a set of vectors of bandwidths allocated to the delivery paths. The set of feasible solutions is constrained by the available bandwidths of the delivery paths. This implies that if the region of feasible solutions is compact and convex then exactly one optimal solution exists. This solution maximizes the quality experience of all clients for every given bandwidth that can be shared among several clients without starving any of them.

Although further investigations into feasible additive expressions for video quality estimation are necessary, we can already show how far the optimal allocation of video quality diverges from optimal allocations of bandwidth with this simple concave utility function.

We define a utility function that expresses quality of multiple videos as a sum of qualities perceived by all clients in the system. Due to the concavity of Eq. 4 and the convexity and compactness of the feasible region, as shown by the inequalities 9, 10, 11, and 12, the solution of the optimization problem is a unique vector. Due to logarithmic nature of the video quality, it is also proportionally fair as shown by Kelly [12]. This implies that the maximization of the utility function can be achieved by sharing bandwidth fairly. This has been an active research question whose answers we should revisit to understand their relation to the optimization of video quality of a group of clients.

V. BENCHMARKS

We defined the network model and the mathematical model for the benchmark system, that optimizes the assignment of the available bandwidths to multiple streams, earlier in [2]. For the sake of completeness, we give a short summary of the model in this section. We also extend it with a new utility function for video quality of a group of clients. The formulation of the problem is simular to a multi-commodity path-flow formulation [**?**]. However, in our case, we need to consider two graphs representing both the underlay and overlay networks. The bandwidth limitations of the underlay arcs that are shared by several overlay paths and that constrain the rate allocation process are not trivially capturable in the overlay graph. It implies that we need to reformulate the problem to address also the underlay properties.

To build our benchmarking system, we model the network that includes senders, receivers and overlay nodes as a graph $D = (V, A)$, where V is the set of vertices that represent the nodes of the network, and A is the set of arcs that represent the links between the nodes. The sets $V_s, V_o, V_r \in V$ are disjoint subsets of vertices representing respectively sender, overlay and receiver nodes. In the graph D, we define a set of all possible paths between the receivers and the senders. This includes the direct paths between the senders and the receivers and the paths that are constructed in the overlay plane using all possible permutations of the overlay nodes.

$$b : A \rightarrow R_0^+ \tag{5}$$

$$b(p) = \min\{b(a)\}, a \in p \tag{6}$$

$$\delta(a,p) = \begin{cases} 1, \text{if} & a \in p \\ 0, \text{if} & a \notin p \end{cases} \tag{7}$$

$$\max \sum_{p_{i,j}^k \in P} f(x_{i,j}^k) \tag{8}$$

$$\forall \{i,j\} : \sum_{k=0,K_{i,j}} x_{i,j}^k \cdot r_{i,j} \geq r_{i,j}^b \tag{9}$$

$$\forall \{i,j\} : \sum_{k=0,K_{i,j}} x_{i,j}^k \leq 1 \tag{10}$$

$$\forall \{a\} : \sum_{p_{i,j}^k \in P} x_{i,j}^k \cdot r_{i,j} \cdot \delta(a, p_{i,j}^k) \leq b(a) \tag{11}$$

$$\forall \{p\} : x_{i,j}^k \cdot r_{i,j} \leq b(p_{i,j}^k) \tag{12}$$

Table I
BENCHMARK MODEL

Then, $p_{i,j}^k$ denotes the k-th path in the set of paths connecting the sender i with the receiver j. $K_{i,j}$ denotes the number of paths from the sender i with the receiver j.

To model network resources and constraints, we have used the formulas defined in Table I. First, we define the bandwidth function on the underlay arcs that expresses the available bandwidth of the arc a using Eq. 5. The same function is defined on the paths where the available bandwidth of a path p is defined as the lowest bandwidth among all arcs that belong to the path p (Eq. 6). Then, for each path p and each ark a, we define a function δ in Eq. 7.

Furthermore, the streaming requirements of the requested streams are defined by a matrix R, where an element $r_{i,j}$ represents the required bitrate at which the stream from the sender v_s^i is streamed to the receiver v_r^j. In addition, we define the matrix R^b which is similar to the above matrix R, but contains the bitrates for the base layers. The variable $x_{i,j}^k$ denotes the share of the multimedia stream that is sent from the content provider v_S^i to the receiver v_R^j through the path k, and with this we can define the utility function in Eq. 8 as a function of bitrates assigned to the paths. In the paper, we consider two utility functions. The first one is a linear function that maximizes the bandwidth assigned to all streams in the system. The second one is a logarithmic utility function that is defined as a sum of video qualities experienced by all users of the system.

The utility functions are subject to the set of constraints given in Eqs. 9-12. First, in order to be able to play out the video, each session requires at least bandwidth for the base layer (Eq. 9). Second, the sum of sending rates along all paths from one sender to one receiver should not exceed the bitrate assigned to this stream (Eq. 10). Third, with respect to shared underlay links, the total sending rate must not exceed the available bandwidth of the shared link (Eq. 11), and finally, the bitrate assigned to the path should not exceed the bandwidth of the path (Eq. 12).

The latency function is not considered in the model, as the overlay paths that have high latency can benefit to the streaming process at later moment.

VI. EXPERIMENTS

We apply the benchmarks to several network scenarios to compute the optimal bandwidth assignment. The computation is based on the system of inequalities defined in Table I and two utility functions. One utility function is a logarithmic function defined as video quality of a group of clients in Section IV, and the second one is a linear function defined as a sum of bitrates assigned to all clients in [2].

We applied the benchmarks to several network topologies and different clients requests. For each of these topologies, the bandwidth of the links has been degraded gradually several times, and the benchmarks for each of these degraded trials have been computed. To stress the network in a controlled manner and to demonstrate that the benchmarks redistribute the bandwidth to achieve the corresponding optimum, we have chosen to degrade the bandwidth of the links manually rather than doing it randomly for the longer sequences of changes.

In the first example, we use a symmetric network topology consisting of two senders, four receivers and three overlay nodes, depicted in Figure 2. All clients request the same bandwidth. Both the linear and the logarithmic benchmarks give the same results.

The second example uses the same network topology, number and placement of the senders, overlay nodes, and receivers as the first example. However, in the second example, there are two types of receivers requesting different amounts of bandwidth: One type requests streams at 400 kbps, and the second type requests streams at 900 kbps. Each sender streams video to one 400 kbps client and one 900 kbps client. The results are depicted in Figure 3(a) and Figure 3(b). The x-axes represent the trials for each link bandwidth degradation, the y-axes represent the assigned bandwidth. The results show that the logarithmic benchmark distributes the bandwidth more equally among the clients following the proportionally fair allocation, and it also results in higher achieved video quality (see Figure 3(c)).

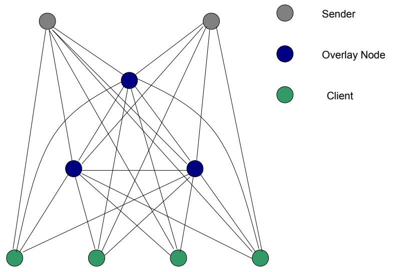

Figure 2. Symmetric overlay network

The third example uses three senders, three overlay nodes and six receivers that were randomly placed in a Waxman topology consisting of 100 nodes, generated by the Brite topology generator [16]. Waxman topologies are considered a fairly realistic approximation of real-world networks. The results are depicted in Figure 4(a) and Figure 4(b). The benchmark results in this example are simular to the allocation results for symmetric topology. As Figure 4(c) shows, the logarithmic benchmark achieves better results in terms of video quality, and allocates the available bandwidth proportionally fair among the clients.

VII. CONCLUSION AND FUTURE WORK

We have addressed the problem of how the available bandwidth can be allocated in a multipath multisource overlay system. We have presented and compared two benchmarks for evaluating multipath rate allocation algorithms. In the first benchmark, the linear utility function maximizes the bandwidth assigned to all streams in the system. For the second benchmark, we have defined a logarithmic utility function that expresses the video quality of multiple users.

The function in Eq. 4 that we used for defining the logarithmic utility function works well for the purpose of this paper, namely providing the proportionally fair allocation of the available bandwidths among the clients and for comparing the linear and logarithmic benchmarks. However, it is an approximation for evaluating the video quality and, in our future work, we intend to define more realistic estimations for perceived video quality.

Our experiments show that the second benchmark provides better bandwidth allocation in terms of achieved video quality over the whole set of users while providing the same optimal solution in terms of utilization of available bandwidth. The logarithmic benchmark is also proportionally fair in allocating available bandwidth to different clients.

We plan to implement similar benchmarks for evaluating multicast multipath algorithms, and also consider optimal placement of caching proxies. Since the calculation of these benchmarks is compute-intensive, and since the knowledge of the entire system state is necessary for the calculation, we will use them only to compare the rate allocation algorithms with the optimal case provided by this work. Further, we intend to develop distributed algorithms both for unicast and multicast streaming and evaluate them using the developed benchmarks. These algorithms are then to be integrated into the overlay node together with other basic streaming functionalities. These can include stream caching, transcoding of multimedia content, error correction mechanisms.

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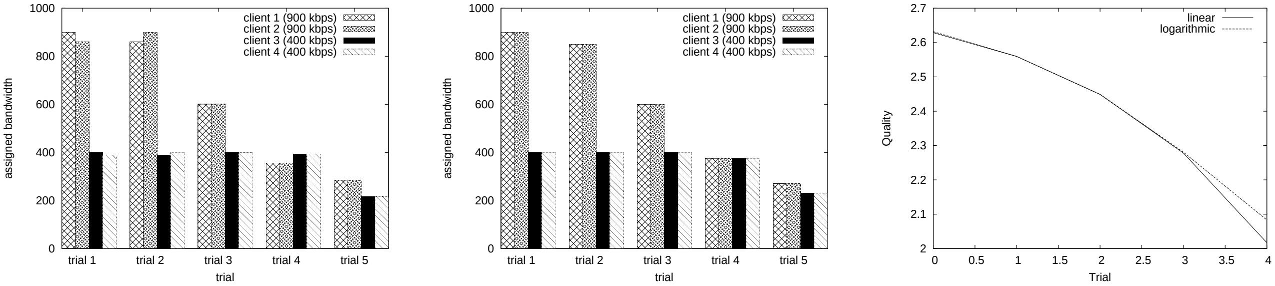
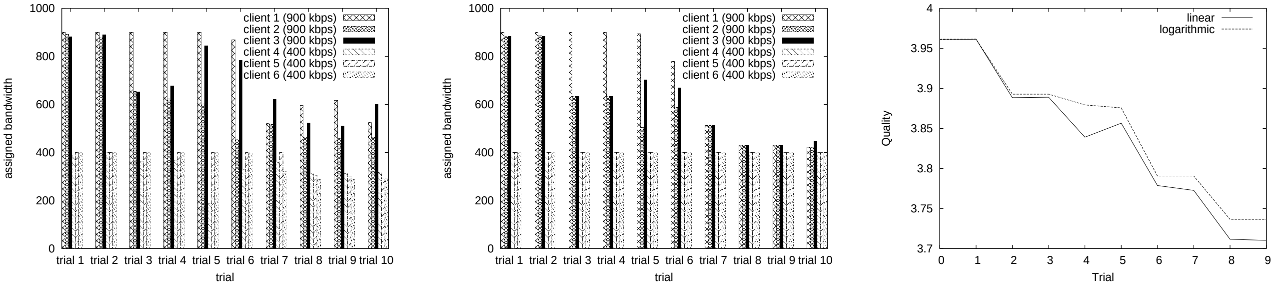


(a) Optimization with linear utility function (b) Optimization with logarithmic utility function (c) Logarithmic utility

Figure 3. Symmetric network with decreasing total bandwidth



(a) Optimization with linear utility function (b) Optimization with logarithmic utility function (c) Logarithmic utility

Figure 4. Random network with decreasing total bandwidth

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