QoE Optimization Through In-Network Quality Adaptation for HTTP Adaptive Streaming

Niels Bouten*, Jeroen Famaey*, Steven Latré*,
Rafael Huysegems†, Bart De Vleeschauwer†, Werner Van Leekwijck† and Filip De Turck*
*Ghent University - IBBT - IBCN - Department of Information Technology
Gaston Crommenlaan 8/201, B-9050 Gent, Belgium, e-mail: niels.bouten@intec.ugent.be
†Alcatel-Lucent Bell Labs, Copernicuslaan 50, B-2018 Antwerpen, Belgium

***Abstract*—HTTP Adaptive Streaming (HAS) is becoming the de-facto standard for adaptive streaming solutions. In HAS, video content is split into segments and encoded into multiple qualities, such that the quality of a video can be dynamically adapted during the HTTP download process. This has given rise to intelligent video players that strive to maximize Quality of Experience (QoE) by adapting the displayed quality based on the user's available bandwidth and device characteristics. HAS-based techniques have been widely used in Over-the-Top (OTT) video services. Recently, academia and industry have started investigating the merits of HAS in managed IPTV scenarios. However, the adoption of HAS in a managed environment is complicated by the fact that the quality adaptation component is controlled solely by the end-user. This prevents the service provider from offering any type of QoE guarantees to its subscribers. Moreover, as every user independently makes decisions, this approach does not support coordinated management and global optimization. These shortcomings can be overcome by introducing additional intelligence into the provider's network, which allows overriding the client's decisions. In this paper we investigate how such intelligence can be introduced into a managed multimedia access network. More specifically, we present an in-network video rate adaptation algorithm that maximizes the provider's revenue and offered QoE. Furthermore, the synergy between our proposed solution and HAS-enabled video clients is evaluated.**

I. INTRODUCTION

The consumption of multimedia services over the Internet has recently witnessed an important evolution. The increase in popularity of Over-the-Top (OTT) video services has led to the adoption of HTTP-based streaming technologies. This shift in technologies was mainly induced by the advantages offered by streaming over HTTP: the reuse of caching infrastructure, the reliable transmission and the compatibility with firewalls.

Initially, HTTP-based video protocols required downloading the complete video before it could be played. Afterwards, progressive download techniques using buffers to store a few seconds of video in advance allowed playback to start after only a fraction of the video was downloaded. However, when congestion in the network varies, these techniques are not able to cope with buffer starvation, leading to frame freezes and stuttered playback. The third evolution in HTTP-based streaming techniques tackles these shortcomings by splitting the content in small segments that are encoded at multiple quality rates. This allows intelligent video clients to adapt the downloaded qualities to the current network state, such as network throughput and delay. These HTTP Adaptive Streaming (HAS) techniques are now becoming the de-facto standard for adaptive streaming solutions.

Recently, academia and industry have started investigating the merits of adopting HAS in managed IPTV scenarios. However, the revenue opportunities that HAS-services offer to network and service providers come with important new management challenges. The adoption of HAS in a managed environment is complicated by the fact that the quality adaptation component is fully controlled by the end-user. This prevents providers from offering any type of Quality of Experience (QoE) guarantees to their subscribers. Moreover, as every user independently adjusts its quality, there is no support for coordinated management and global optimization. When a provider thus offers different subscription levels (i.e., Diamond, Gold, Silver, Bronze, Free), there is no possibility to enforce management policies related to the user's subscription terms. We therefore propose to overcome these shortcomings by introducing additional intelligence in the provider's network. This allows the provider to influence the client's decisions and manage the offered QoE.

The contributions of this paper are three-fold. First, we implemented a simulator for HAS-based video delivery based on NS-3. Second, a Linear Programming (LP) model is defined to enforce different management policies for maximizing the provider's revenue and offered QoE. Third, we present extensive simulation results to evaluate the approach by demonstrating the impact of the in-network management on obtained revenue and QoE. Furthermore we compare these results with HAS-enabled clients and evaluate the synergy between the proposed approach and these clients.

The remainder of this article is structured as follows. Section II provides an overview of relevant work in the area of management of HTTP Adaptive Streaming. In Section III we provide the general problem definition for the in-network management of quality adaptation. Section IV describes the specific management policies that were used during the evaluation. In Section V the simulation framework and the rate adaptation algorithms are evaluated. Finally, Section VI summarizes the main findings and contributions of this article.

978-3-901882-48-7 ©2012 IFIP

II. RELATED WORK

The recent advent of video consumption over the Internet has led to the development of several protocols that allow dynamic adaptation of the quality rate of a HTTP-based video session. Some of the major players have introduced their own protocols, server and client software such as Microsoft's Silverlight Smooth Streaming [1], Apple's HTTP Live Streaming [2], Adobe's HTTP Dynamic Streaming [3] and MPEG's standardized Dynamic Adaptive Streaming over HTTP (DASH) [4]. Although differences exist between these implementations they are all based on the same basic principles: a video is split up into several segments which are encoded at different quality rates, the intelligent video clients then dynamically adapt the quality, based on metrics such as average throughput, delay and jitter.

The drawback of this approach is off course that all QoE control lays in the hands of the clients which strive to maximize their individual QoE. From the provider's perspective however, other factors such as minimization of costs and prioritisation of users with higher subscription levels are of equal importance. Current HAS approaches do not support intervention in the quality assignment process which is fully dominated by the clients. The approach presented in this paper focuses on global optimization of QoE offered to the clients subject to the costs incurred by violating the user's terms or the utility experienced by the user. This off course requires the presence of a managed network.

Recently, the standardization of the extension to the widely used video coding standard H.264/AVC called Scalable Video Coding (SVC) [5] has led to an increased adoption of this encoding scheme. This also induced the adoption of SVC in HAS by the development of new client heuristics using the specific properties of SVC such as the incremental characteristics of these videos [6]. The proposed approach adapts the buffer-filling strategy based on the measurement of network characteristics such as throughput, delay and jitter, but does not allow global optimization of QoE. In our approach we do not enable buffering by the client heuristic in order to abstract from buffering influences. Instead we use a weighted moving average of download statistics to predict future throughput [7].

Begen et al. argue that the use of adaptive streaming is an important driver for OTT video services and identify some future research directions such as tackling the scalability bottleneck when clients access services concurrently and the necessity for providers to introduce intelligent network elements to improve the performance of offered video services [8]. In contrast to cable TV and IPTV services offered by service providers, running over managed networks with multicast transport and QoS-support, HTTP Adaptive Streaming technologies are mostly unmanaged services running over best-effort networks. In [9] we proposed shifting part of the HAS delivery process to the managed network and exploiting the multicast support to tackle scalability issues in a Live TV setting.

In [10] an overview of interesting use cases for applying SVC in a network environment are presented, among which the graceful degradation of videos when the network load increases. The authors argue the need for Media Aware Network Elements (MANEs), capable of adjusting the SVC stream based on a set of policies specified by the network provider. In [11] a prototype of an intermediary adaptation node is proposed, where the media gateway estimates the available bandwidth on the client link and extracts the supported SVC-streams. Our approach focusses on application layer measures, not only using network parameters such as throughput but also considering the service level of each client, allowing to provide a managed streaming service. Network optimizations for SVC-streaming have been applied on lower layers as well. In [12] and [13] the use of SVC has been optimized for wireless networks. The focus lays on quality adaptation while achieving the highest possible QoS levels in terms of packet loss and delay. We focus on enforcing a specific policy defined by the provider that allows differentiation between the provided service of different subscription levels.

In order to perform the provider's global optimization, we define several management policies based on the utility experienced by the user and the costs incurred by violating their subscriptions' terms. Similar functions have been proposed in literature before, but to our knowledge none of them focusses on service-level dependent goal functions. In [14], Krishnamurthy et al. propose a pricing mechanism for SVC delivery for characterizing the costs of bandwidth allocations. A utility function based on the allocated bandwidth is also provided. In [15] the utility for a user in a P2P system is modelled as a logarithmic function approximating the corresponding PSNR-values, without support for service-level dependencies. Our approach differs from these since we use a mapping of PSNR-values to sMOS-scores and associate them with certain quality levels. Furthermore, we define a utility function which is service level dependent. Krasic et al. [16] define utility as a function of temporal and spatial resolution and introduce dependencies on the video at hand. For simplicity we only used one video and based the utility mapping only on its spatial characteristics, letting the utility function depend on other specific characteristics of the video could enhance the solution's precision.

III. RATE ADAPTATION ALGORITHM

A multimedia delivery network typically consists of a content server and several intermediate proxies. These proxies serve as brokers towards the clients and typically support caching. We introduce additional distributed intelligence here to manage the QoE. The goal of the rate adaptation algorithm at the proxy is to determine the maximum quality each client is allowed to download, taking into account the available outbound bandwidth at the proxy while optimizing a particular objective. The objective under consideration is subject to the management policy determining whether to optimize global QoE or the QoE for a certain group of customers. The specific focus of our algorithm is on the differentiation between users and their respective service levels. Each client is assigned a minimal quality service level, based on its subscription, which the operator needs to guarantee. This allows us to differentiate the service delivery based on the client's subscription. Whenever a client is assigned a quality level lower than this agreed minimum, the operator needs to pay a certain penalty for violating the terms of the service agreement. Each time a new client connection is set up or terminated, the rate adaptation is performed. The proxy advertises to each client their assigned quality level. This could be done by rewriting the manfiest files for that client without making changes to the HAS protocol or by adding extra management signalling to the HAS-protocol.

A. *Definition of variables*

The total available outbound bandwidth on the *HAS Proxy* is characterized by β. Assuming a client c with $c = 1..m$ and m the number of clients, paying for a subscription with service level s_c, is currently viewing video v_c, $a_{c,q}$ denotes if client c is assigned a certain quality level q out of the n_q available levels by the *HAS Proxy*. For each video v, there is a video consumption rate $B_{v_c,q}$ associated with each available quality q, which is an indication for the bandwidth a client consumes when downloading the video in that particular quality. $G_{c,q}$ denotes the value that is associated with the policy function when a client c is assigned to download the video in a quality level q rather then the minimum quality level s_c as stated in the subscription agreement.

B. *Integer Linear Programming Formulation*

In order to solve the rate adaptation problem, an integer linear programming (ILP) model is defined, which seeks the solution that optimizes the objective. The objective in this case is to minimize (or maximize, depending on the management policy) the summation stated in (1). The specific objective functions $G_{c,q}$ are dependent on the enforced policy and are further discussed in Section IV. The constraints of the ILP model are the following. First, the total bandwidth consumed by all clients downloading their video at the assigned quality level may not exceed the maximum outgoing bandwidth of the *HAS Proxy* (2). The second constraint states that the number of assigned quality levels $a_{c,q}$ for each client c should be exactly 1 (3). The latter condition can of course only hold if the available bandwidth is able to provide for each client c, the video v_c at the lowest quality level ($q = 0$) so all clients are admitted (4).

$$\min(or\max)\sum_{c=0}^{m}\sum_{q=0}^{n_q} G_{c,q} * a_{c,q} \tag{1}$$

$$rcl\sum_{c=0}^{m}\sum_{q=0}^{n_q} B_{v_c,q} * a_{c,q} \quad \leq \quad \beta \tag{2}$$

$$\forall c \in [0,m]\sum_{q=0}^{n_q} a_{c,q} \quad = \quad 1 \tag{3}$$

$$\sum_{c=0}^{m} B_{v_c,0} \quad \leq \quad \beta \tag{4}$$

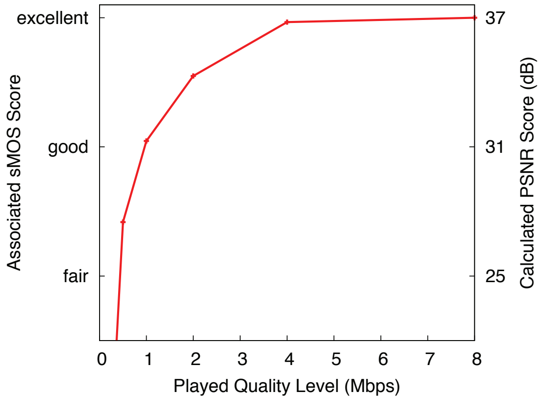

Fig. 1. Mapping of video qualities to calculated PSNR-values and their associated sMOS-estimations.

IV. MANAGEMENT POLICY DEFINITION

Different management policies can be defined to solve the optimization problem depending on whether one wants to maximize the QoE experienced by all users or minimize the penalties incurred by violating the subscription's contract. In this section we propose three goal functions: (i) a function based on the per segment Mean Opinion Score (sMOS), (ii) a function evaluating the utility a user experiences relative to its subscription contract and (iii) one minimizing the penalties incurred by violating the client's contract. We propose 5 different service levels: *Diamond*, *Gold*, *Silver*, *Bronze*, and *Free* with respective video rates of 8Mbps, 4Mbps, 2Mbps, 1Mbps, and 512kbps.

A. *Global Quality Optimization*

A first optimization objective could be to optimize the global QoE perceived by each user, independent of its subscription level. This means treating every user equally and trying to optimize the global perceived quality in terms of MOS. Since an overall MOS-score for a HAS viewing session cannot be derived due to the quality switches, we introduce here the notion sMOS for indicating the MOS-score of a particular segment. Traditional HAS solutions tend to show highly fluctuating quality rates when congestion increases. Not only the played quality and the corresponding sMOS scores are thus important indicators for QoE, but also the stability of the segment quality is a determining factor in evaluating QoE for HAS in congested networks [17]. The videos were encoded using a SVC encoder, after which the PSNR-values of each segment were calculated. Based on these values, the corresponding sMOS-scores were derived using the guidelines stated in Klaue et al. [18] where PSNR-ranges are mapped on MOS scores. Figure 1 illustrates the relationship between the calculated PSNR-values per quality and their corresponding sMOS-scores. The obtained mapping from quality levels to sMOS-scores is used as an objective function:

$$G_{c,q} = sMOS(a_{c,q}) \tag{5}$$

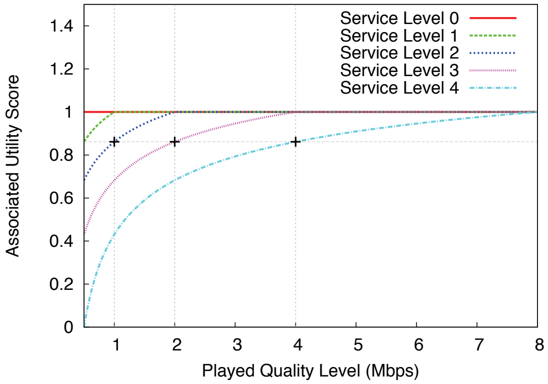

Fig. 2. Plot of the utility-function for clients with different service levels and assigned quality rates displaying the property defined in (6).

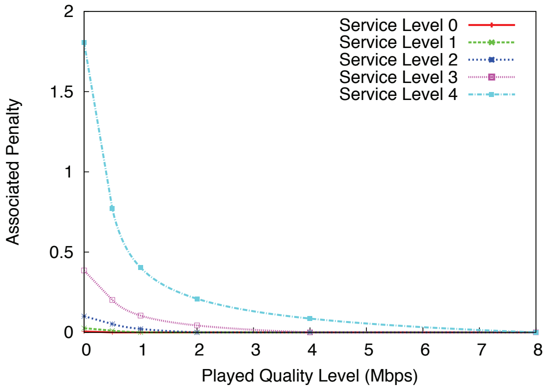

Fig. 3. Plot of the penalty-function for clients with different service levels and assigned quality rates.

B. *User-centric Optimization*

The second proposed management policy is user-centric and tries to maximize the client's utility relative to its subscription level. The user utility function is treated as a measure of the user satisfaction and is modeled as a normalized function where the marginal user utility decreases as the assigned quality approaches the quality level stated in the client's subscription. Unlike sMOS, user utility remains constant when the service level is reached. This means that clients c_a with service level $s_{c_a} > s_{c_b}$ experience lower utility than clients c_b when downloading the same quality level $q < s_{c_a}$. Independent of the service level, the clients experience the same utility drop when switching down an equal amount of quality levels:

$$G_{c_1,q_1} = G_{c_2,q_2} \quad \text{if } s_{c_1} - q_1 = s_{c_2} - q_2 \tag{6}$$

The behavior or the utility function illustrated in Figure 2 and is defined using a logarithmic function following [15]:

$$G_{c,q} = \begin{cases} \dfrac{\log(n_q + q - s_c)}{\log n_q} & \text{if } a_{c,q} = 1 \text{ and } q < s_c \\ 1 & \text{if } a_{c,q} = 1 \text{ and } q \geq s_c \end{cases} \tag{7}$$

C. *Operator-centric Optimization*

The last optimization objective minimizes the penalties an operator has to pay when infringing the client's subscription terms. We propose a penalty function where violating higher subscription levels' terms incur penalties proportional with the denied service. This heavily favors the resource provision for higher level subscriptions. When defining the penalty function for calculating the incurred cost of violating the user's terms, several assumptions about its properties are made. First off, when the assigned quality level approaches the service quality level, the penalty should become zero:

$$\lim_{q \to s_c} G_{c,q} = 0 \quad \text{if } a_{c,q} = 1 \tag{8}$$

Second, the difference between penalties incurred by assigning quality q_1 instead of q_2 should be larger than assigning q_2 instead of q_3 whenever $q_1 < q_2 < q_3$ holds:

$$G_{c,q_1} - G_{c,q_2} > G_{c,q_2} - G_{c,q_3} \quad \text{if } q_1 < q_2 < q_3 \tag{9}$$

Lastly, when considering clients c_1 and c_2 with service levels $s_{c_1} > s_{c_2}$ and qualities q_1 and q_2 so that $s_{c_1} - q_1 = s_{c_2} - q_2$, the penalty for assigning q_1 to the clients c_1 needs to be sufficiently high so that it equals or exceeds the penalty for switching n clients c_2 down to quality q_2. This is necessary in order to free enough bandwidth to sustain providing the clients c_1 with the highest possible quality. Since qualities provided by a certain service level are of the form $2^{s_c+9}kbps$, n is equal to $2^{s_{c_1}-s_{c_2}}$. For example, if clients identified by c_1 have subscription level $s_{c_1} = 4$ meaning that they pay for viewing videos at a rate of 8Mbps but are currently viewing video at a rate of 4Mbps and clients c_2 have level $s_{c_2} = 1$ and are currently viewing 1Mbps video. In order to allow a client c_1 to switch one quality up, at least 8 ($n = 2^{s_{c_1}-s_{c_2}} = 2^{4-1} = 8$) clients c_2 need to switch down to a lower quality level (512kbps) to provision enough bandwidth for a single client c_1 to switch up. Thus the following condition needs to hold:

$$G_{c_1,q_1} \geq 2^{s_{c_1}-s_{c_2}} G_{c_2,q_2} \quad \begin{array}{l} \text{if } s_{c_1} > s_{c_2} \\ \text{and } s_{c_1} - q_1 = s_{c_2} - q_2 \end{array} \tag{10}$$

Taking al these conditions into account, the following penalty function is defined:

$$G_{c,q} = \begin{cases} 2^{s_c - n_q + 1}\left(\dfrac{\log(n_q + 2)}{\log(n_q + q - s_c + 2)} - 1\right) \\ \quad \text{if } a_{c,q} = 1 \text{ and } q < s_c \\ \\ 0 \\ \quad \text{if } a_{c,q} = 1 \text{ and } q \geq s_c \end{cases} \tag{11}$$

Figure 3 illustrates the properties of this function.

V. PERFORMANCE EVALUATION

A. *Simulation framework*

In order to perform a realistic evaluation of the characteristics of the different quality selection approaches, a packet-based simulator was built upon NS-3. Figure 4 gives

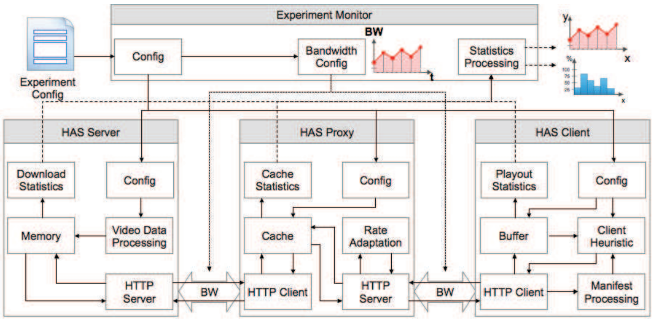

Fig. 4. Overview of the NS-3 based HAS simulator framework.

a conceptual overview of the work-flow of this simulator. Three main components exist: (i) a *HAS Server* taking realistic video statistics as input, such as the number of segments and their corresponding sizes (ii) a *HAS Proxy* acting as a broker towards the clients for the *HAS Server* and (iii) a *HAS Client* requesting videos at certain quality levels and outputting the related statistics concerning received quality, delay, perceived sMOS and quality switches. All these components communicate over HTTP using a NS-3 channel with configurable characteristics such as available bandwidth and end-to-end delays.

The quality selection heuristic used in the implementation of the *HAS Client* is based upon an existing heuristic called Priority-Based Media Delivery [7] and decides which quality to download by considering several previously downloaded fragments through a weighted moving average. The enforcement of quality selection when using the ILP-based solution by the *HAS Proxy* is accomplished by only advertising quality rates up to the assigned level for that specific *HAS Client*. The IBM CPLEX solver was used to implement and solve the proposed binary ILP-problem [19].

B. Experiment setup

Figure 5 shows the experiment setup used during the evaluation with 50 clients connecting to a *HAS Proxy* acting as a broker for the *HAS Server*. Each of these clients connects to a router via a 20Mbps link and sharing a 100Mbps link to the *HAS Proxy*. The link between the *HAS Server* and *HAS Proxies* is provided with sufficient bandwidth so to minimize the fluctuations in download rates for the *HAS Clients*. A single experiment consists out of several phases: (i) during the ramp-up phase, 50 clients per proxy are started randomly in a 100 second interval, this phase is followed by (ii) a steady-state phase which lasts for several minutes and is followed by (iii) the ramp-down phase during which clients are shut down with a 2 second interval. We performed 20 iterations per experiment and calculated the average values and their standard deviations. The different subscription levels are spread uniformly over the client population leading to 5 groups of clients requesting respectively videos of 512kbps, 1Mbps, 2Mbps, 4Mbps, and 8Mbps. Four configurations are tested: HAS, where all intelligence resides at the *HAS Clients*, HAS+USER-C, HAS+OPER-C and HAS-GLOBAL, where the *HAS Proxy* is enabled, using the optimization functions as defined in Section IV and interacting with the adaptation control at the client. When intelligence at the *HAS Proxy* and *HAS Client* are combined, the proxy advertises to each client their assigned levels. The clients can then adjust their downloaded qualities up to that specified level.

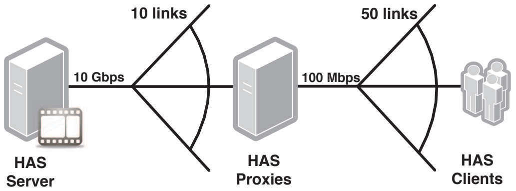

Fig. 5. Experiment setup showing how multiple *HAS Clients* connect over a shared link to the *HAS Proxy*.

C. Impact of Management Policy

Figure 6 illustrates the average sMOS-scores for the different strategies subject to the service level of the clients. It shows how HAS and HAS+GLOBAL try to optimize the perceived quality independent of the client's service level. While operator-centric optimization strongly favors higher level subscriptions at the cost of lower level subscriptions downloading lower qualities. The service levels 0 and 1 both receive video at an average sMOS level of 3.4178, which corresponds to downloading the lowest quality (512kbps). All clients with service level 1 are switched down to service level 0 to free up bandwidth for higher level subscriptions. When optimizing the average utility (HAS+USER-C) higher level subscriptions are favored but only up to a certain level, since the utility does not increase exponentially as the served qualities do.

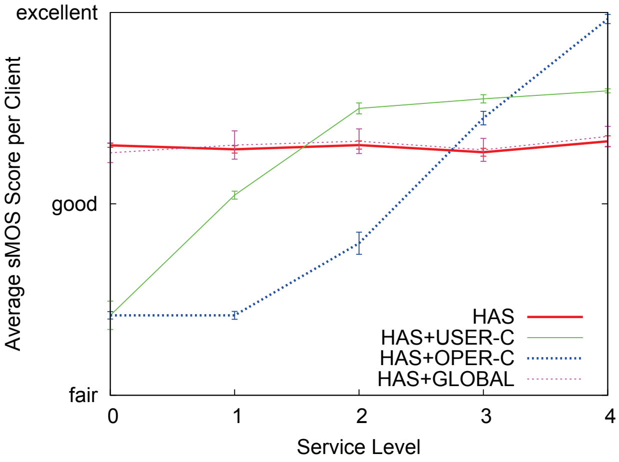

Fig. 6. Average sMOS-scores per client relative to the subscription level.

Figure 7 illustrates the average incurred penalties per service level. Both the HAS+OPER-C and HAS+USER-C perform well when the service level increases. HAS and HAS+GLOBAL do not take subscription level into account and incur penalties that are twice as high compared to using operator-centric optimization. The operator-centric optimization incurs higher penalties for the lower level subscriptions,

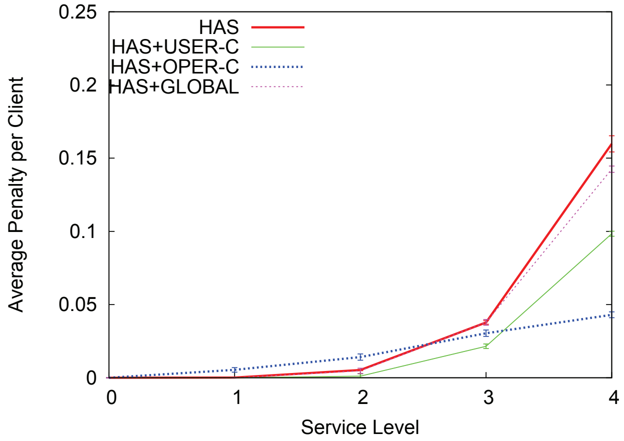

Fig. 7. Average penalty per client under at different subscription levels.

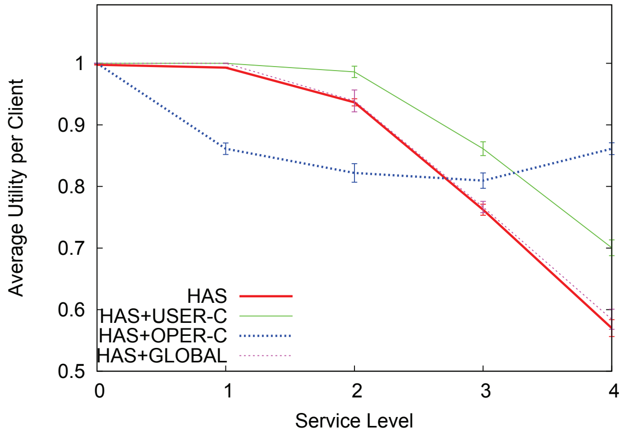

Fig. 8. Average utility per client at different subscription levels.

since they are more likely to be assigned a lower quality than the higher level ones. Figure 8 shows the average utility perceived by the client, per service level. It shows how the operator-centric optimization yields higher utility for the higher level subscriptions.

Figure 9 shows the average percentage of clients switching during a 10s interval. Traditional HAS-solutions with the intelligence fully residing at the *HAS Clients*, show high switching percentages with peaks of almost 60% of the clients switching and an average of 11.75% of the clients switching. Other solutions show very stable behavior with nearly zero quality switches. Since the quality fluctuations during video playout also form an important factor of the perceived QoE for the end-user, these results plead for the adoption of more intelligent network elements determining the optimal rates in HAS-based streaming applications.

VI. Conclusion and Future Work

In this paper we characterized the merits of deploying intelligent network elements that manage the QoE in HAS delivery networks. This allows a network provider to assign certain quality levels to specific clients subject to their respective subscription terms. We proposed different optimization policies such as the sMOS-score experienced by the client, the utility as function of the client's service level and the penalties incurred by violating the contract terms when assigning a lower quality rate. All of these solutions were implemented in a simulation framework based on NS-3 and extensively evaluated. Both the original HAS-based solution and the combination of the policy-based solutions with HAS-enabled clients were evaluated. We argue that a combination of HAS enabled clients with the operator-centric of user-centric policy enforced at the intelligent proxies leads to the best solution, since they tend to optimize the perceived quality in terms of sMOS-score and stability relative to the subscription level. We showed that the application of in-network operator-centric optimization favors allocation of available bandwidth to higher level subscriptions and thus decreases the global penalty with 50%, while maximizing the QoE in terms of sMOS for the higher level subscription. Furthermore the in-network optimization leads to a far more stable quality selection compared to pure HAS quality heuristics (less than 1% of clients switching compared to more than 11.75% switching). In future work, the utility and penalty functions could be improved to reflect a more realistic behavior by running user trials to determine actual perceived utility. Also, a video reconstruction element should be added to the simulator to be able to employ state of the art quality metrics. Furthermore, a techno-economic study would be interesting to assess the impact on the costs for the provider to deploy our proposed management scheme, in terms of infrastructure as well as customer retention. The simulations could also benefit from more realistic configurations reflecting to statistics from operational services.

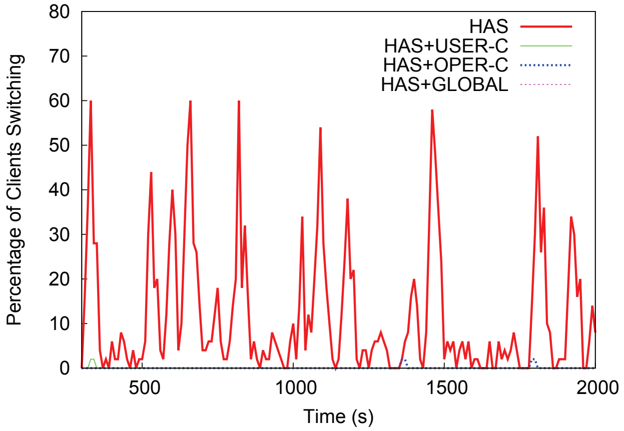

Fig. 9. Percentage of clients switching per 10s interval under different configurations.

Acknowledgment

Steven Latré is funded by grant of the Fund for Scientific Research, Flanders (FWO-V). The research was performed partially within the IBBT MISTRAL project (under grant agreement no. 10838). The Alcatel-Lucent research was performed partially within IWT project 110112.

REFERENCES

[1] Microsoft, "Smooth streaming: The official microsoft IIS site." [Online]. Available: http://www.iis.net/download/SmoothStreaming

[2] R. Pantos and W. May, "HTTP Live Streaming," 2011. [Online]. Available: http://tools.ietf.org/html/draft-pantos-http-live-streaming-07

[3] Adobe, "HTTP dynamic streaming: Flexible delivery of on-demand and live video streaming." [Online]. Available: http://www.adobe.com/products/httpdynamicstreaming/

[4] T. Stockhammer, "Dynamic adaptive streaming over HTTP: standards and design principles," in *Proceedings of the second annual ACM conference on Multimedia systems*, ser. MMSys '11. New York, NY, USA: ACM, 2011, pp. 133–144. [Online]. Available: http://doi.acm.org/10.1145/1943552.1943572

[5] H. Schwarz, D. Marpe, and T. Wiegand, "Overview of the scalable video coding extension of the H.264/AVC standard," in *IEEE Transactions on Circuits and Systems for Video Technology In Circuits and Systems for Video Technology*, 2007, pp. 1103–1120.

[6] T. Andelin, V. Chetty, D. Harbaugh, S. Warnick, and D. Zappala, "Quality selection for dynamic adaptive streaming over HTTP with scalable video coding," in *Proceedings of the 3rd Multimedia Systems Conference*, ser. MMSys '12. New York, NY, USA: ACM, 2012, pp. 149–154. [Online]. Available: http://doi.acm.org/10.1145/2155555.2155580

[7] T. Schierl, Y. Sanchez de la Fuente, R. Globisch, C. Hellge, and T. Wiegand, "Priority-based media delivery using SVC with RTP and HTTP streaming," *Multimedia Tools and Applications*, vol. 55, pp. 227–246, 2011. [Online]. Available: http://dx.doi.org/10.1007/s11042-010-0572-5

[8] A. Begen, T. Akgul, and M. Baugher, "Watching video over the web: Part 1: Streaming protocols," *Internet Computing, IEEE*, vol. 15, no. 2, pp. 54–63, 2011.

[9] N. Bouten, S. Latré, W. V. de Meerssche, K. D. Schepper, B. D. Vleeschauwer, W. V. Leekwijck, and F. D. Turck, "An autonomic delivery framework for HTTP adaptive streaming in multicast-enabled multimedia access networks." in *NOMS*. IEEE, 2012, pp. 1248–1253. [Online]. Available: http://dx.doi.org/10.1109/NOMS.2012.6212059

[10] T. Schierl, C. Hellge, S. Mirta, K. Gruneberg, and T. Wiegand, "Using h. 264/avc-based scalable video coding (svc) for real time streaming in wireless ip networks," in *IEEE International Symposium on Circuits and Systems, ISCAS 2007*. IEEE, 2007, pp. 3455–3458.

[11] Y. Hsiao, S. Yeh, J. Chen, and Y. Chu, "A design of bandwidth adaptive multimedia gateway for scalable video coding," in *IEEE Asia Pacific Conference on Circuits and Systems (APCCAS), 2010*. IEEE, 2010, pp. 160–163.

[12] C. Foh, Y. Zhang, Z. Ni, J. Cai, and K. Ngan, "Optimized cross-layer design for scalable video transmission over the IEEE 802.11 e networks," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 17, no. 12, pp. 1665–1678, 2007.

[13] K. Tappayuthpijarn, T. Stockhammer, and E. Steinbach, "A novel co-ordinated adaptive video streaming framework for scalable video over mobile networks," in *17th IEEE International Conference on Image Processing (ICIP), 2010*. IEEE, 2010, pp. 2893–2896.

[14] A. Krishnamurthy, T. Little, and D. Castaon, "A pricing mechanism for scalable video delivery," *Multimedia Systems*, vol. 4, pp. 328–337, 1996. [Online]. Available: http://dx.doi.org/10.1007/s005300050034

[15] M. Chen, M. Ponec, S. Sengupta, J. Li, and P. Chou, "Utility maximization in peer-to-peer systems," *ACM SIGMETRICS Performance Evaluation Review*, vol. 36, no. 1, pp. 169–180, 2008.

[16] C. Krasic, J. Walpole, and W. Feng, "Quality-adaptive media streaming by priority drop," in *Proceedings of the 13th international workshop on Network and operating systems support for digital audio and video*. ACM, 2003, pp. 112–121.

[17] D. C. Robinson, Y. Jutras, and V. Craciun, "Subjective video quality assessment of HTTP adaptive streaming technologies," *Bell Labs Technical Journal*, vol. 16, no. 4, pp. 5–23, 2012. [Online]. Available: http://dx.doi.org/10.1002/bltj.20531

[18] J. Klaue, B. Rathke, and A. Wolisz, *EvalVid - A Framework for Video Transmission and Quality Evaluation*, ser. Lecture Notes in Computer Science, P. Kemper and W. Sanders, Eds. Springer Berlin / Heidelberg, 2003, vol. 2794.

[19] S. Popinet, "IBM: IBM ILOG CPLEX Optimization Studio V12.4," 2011. [Online]. Available: http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/