# Exploiting Proxy-Based Transcoding to Increase the User Quality of Experience in Networked Applications

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## Abstract

*In this work we describe how we extended the functionality of our previously introduced application and network aware proxy system with transcoding capabilities. Based on their compound awareness, our proxies devise a strategy for every connected client that intelligently distributes the client's available bandwidth over the different application data streams. The proxies subsequently put each computed bandwidth allocation strategy into effect by managing and transcoding data streams inside the network before they reach the client. We also present results from the integration of our work into an existing Networked Virtual Environment. These results clearly indicate that our intelligent proxy, enhanced with its novel transcoding functionality, can increase the user Quality of Experience considerably in networked applications.*

## 1. Introduction

The last few years, we are witnessing an ever increasing heterogeneity in the end-user device space. As a result, users can nowadays choose from a multitude of devices, each with their own specific capabilities and constraints, to connect to the Internet. Examples include desktop PCs, laptops, Personal Digital Assistants (PDAs) and smartphones. While there are many advantages associated with this increased client diversity, it also complicates multimedia content delivery. After all, multimedia content suitable for presentation on a desktop PC often cannot be displayed efficiently on a mobile device.

This problem can be resolved in two different ways. The first solution consists of supplying multiple versions of the same content and providing users with the version that best suits the capabilities of their client device and network connection. For example, content providers could provide both low and high resolution versions of a video fragment. Whenever a wireless PDA user requests this video fragment, he should be served the low resolution version due to the form factor of his device and the low throughput of his network link. On the other hand, whenever a PC user with a broadband Internet connection requests this particular video fragment, he should be served the high quality version. The main drawback of this approach is its lack of flexibility. If a new device is released which has capabilities unlike any of the devices already on the market, this device cannot be served an optimal version of the content unless a new version is explicitly supplied by the content provider. Furthermore, this approach makes content management difficult and error-prone since multiple versions of the same content reside on the origin server.

A second, more dynamic solution consists of transcoding the content on-the-fly to a convenient format before it reaches the end-user. A transcoder can take the constraints of both the transportation network and the receiving end-user device into account when transforming content on behalf of a client. As a result, there is no need to store multiple versions of the same content on the origin server. Furthermore, this approach is also flexible in the sense that content can be adapted in real-time to optimally match the capabilities and constraints of *any* device. On the other hand, an important disadvantage of transcoding is its computational complexity. Transcoding is a very processor intensive task, which can result in scalability issues in case large numbers of simultaneous users need to be supported. Despite this drawback, we believe transcoding to be a very powerful technique whose usability is not confined to content delivery scenarios.

In [21], we discussed the implementation of an extensible software proxy that is both *application* and *network* aware. This means the proxy on the one hand has high-level knowledge of the application it is serving. In case of a Networked Virtual Environment (NVE) or Massively Multiplayer Online Game (MMOG), this application related

knowledge could for instance include information about the positions and orientations of users in the virtual world. On the other hand, the intelligent proxy periodically probes the underlying transportation network to obtain network related information such as the current throughput and packet loss rate of individual network links. In the original version of the proxy, this compound awareness was exploited by a rather basic quality selection plug-in to intelligently manage and control data streams destined for connected clients [21]. This plug-in had a very coarse granularity, since it was only capable of turning data streams on and off.

In this paper, we describe the implementation of a much more flexible plug-in that adds transcoding functionality to our intelligent proxy. Based on its compound awareness, the proxy is now capable of intelligently transcoding data streams to lower quality versions as they become needed by connected clients. Furthermore, we investigate whether our transcoding-enabled proxy could positively affect the user Quality of Experience (QoE) in networked applications such as NVEs and MMOGs. QoE is a subjective measure that relates to the experience people have when they use an application or a product.

The remainder of this paper is organized as follows. In section 2 we review related work on the distributed proxy network architecture and on content-based transcoding (with an emphasis on video transcoding). Section 3 describes the implementation of our intelligent proxy and its video transcoding plug-in. The NVE framework we integrated our work in is introduced briefly in section 4. In section 5 we present some experimental results which clearly demonstrate that our intelligent proxy, enhanced with transcoding functionality, can increase the user QoE considerably in networked applications. This section also describes the approach we employed to maximize the proxy's scalability. Finally, we pose our conclusions and suggest possible future research directions in section 6.

## 2. Related work

In comparison with the client/server and peer-to-peer architectures, the distributed proxy architecture is a relatively new network topology. In this architecture, a number of interconnected proxies are placed at the edge of the network, and clients only communicate with the proxy nearest to them. This is illustrated in figure 1. The main advantages of the distributed proxy architecture are increased system robustness (there is no single point-of-failure in the system) and reduced packet delay (proxies can cache data locally, this way decreasing the amount of time needed for data to reach requesting clients) [2][10]. Furthermore, proxies can perform valuable services such as packet filtering and packet aggregation inside the network, thereby making the

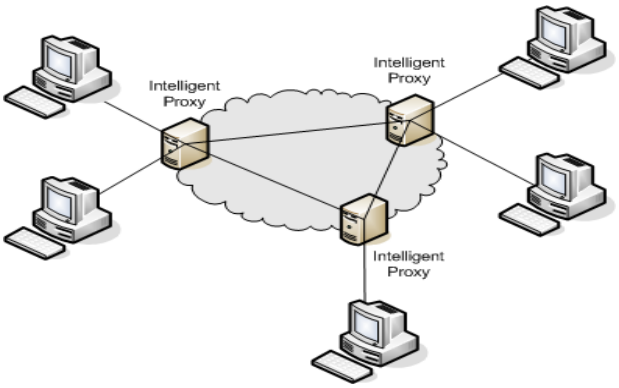



**Figure 1. The distributed proxy network architecture.**

network more intelligent. In [3], the results of porting a popular multi-player FPS game to the distributed proxy architecture are described. Nguyen et al. discuss in [12] how the distributed proxy architecture can be employed to provide immersive audio communication to users of online games. Finally, a flexible and highly modular proxy platform called *AMPS* is introduced in [22]. The platform supports an extensible set of streaming services and has been specifically designed with scalability in mind. However, in contrast to our intelligent proxy, the AMPS proxies at the moment still lack transcoding functionality.

On-the-fly transcoding of content to a convenient format is steadily receiving more and more attention from the research community. This is largely due to the popularization of mobile devices. In [17], an early content-based image transcoder is described which takes the capabilities of the receiving client device and the type and purpose of the image into account. The authors demonstrate clear improvements in both image delivery speed and image accessibility. A transcoding and caching intermediary for web content called *TranSquid* is discussed in [9]. TranSquid tries to increase the user satisfaction by servicing client requests from its cache as much as possible, hereby transcoding the cached content to an appropriate format if necessary. Knutsson et al. introduce in [6] the concept of *server-directed transcoding*, apply it to web content, and show how it can be integrated into the HTTP protocol. In the server-directed transcoding approach, the origin server guides the transcoder to make sure the content does not lose its semantics when it is being adapted to match the capabilities and preferences of the requesting client. Finally, a content transcoding middleware that aims at enabling universal access to military geospatial information (such as maps) is presented in [8]. The middleware represents the geospatial data as Scalable Vector Graphics, an XML-based W3C standard, and uses Java plug-ins and XSL stylesheets to

transcode these SVG files to a format that suits the capabilities and preferences of the requesting client.

The advent of broadband access networks has led to a serious increase in the number of video files accessible through the Internet. This in turn boosted video transcoding research. Vetro et al. give in [20] an excellent overview of video transcoding architectures and techniques for block-based video coding schemes. Bit-rate reduction, spatial and temporal resolution reduction and error-resilience transcoding of video streams are discussed. In [1], a video gateway is presented that addresses the problem of heterogeneous client environments by intelligently transcoding and rate-controlling video streams. Another video transcoding gateway is described in [7]. The specific focus here is to enable video access on mobile devices. Finally, Shen et al. discuss in [15] and [16] their *Transcoding-enabled Caching proxy* (TeC proxy). The TeC proxy performs transcoding as well as caching to improve the efficiency of video delivery to heterogeneous end-users with various network conditions and device capabilities. Furthermore, the authors also introduce three novel caching algorithms which take the transcoding functionality of the proxy into account. The presented results demonstrate that these new algorithms are capable of seriously outperforming traditional caching strategies.

There is a large resemblance between the work we present in this paper and the systems described in [1],[7],[15],[16]. Some of these systems are even more sophisticated in terms of transcoding functionality and transcoding performance. However, the main difference between our work and the referred systems is that the latter focus solely on content delivery. While our intelligent proxy architecture can also be used in content delivery scenarios, it can just as well be integrated in more complex networked applications such as NVEs and videoconferencing programs. This is mainly due to the fact that our proxy, in contrast to the other systems referred in this section, also leverages application related information when making routing and transcoding decisions. We believe application awareness is crucial to provide users of networked applications with a maximal QoE, and we will demonstrate this in section 5.

## 3. Implementation

### 3.1. Intelligent proxy implementation

As described in [21], our proxy system is both application and network aware. In order to gain application awareness, we proposed to insert a *network intelligence layer* (NI layer) between the transport layer and the application layer of the client software. The main responsibility of the NI layer consists of continuously querying the application's awareness management model in order to obtain information regarding the relative importance of the different data streams present in the system. This information is subsequently transmitted to the proxy this client is connected to. For example, in case of an NVE, the awareness management model could specify that data streams belonging to objects which are located close to the local user in the virtual world have a higher significance than streams belonging to more distant objects. Since the NI layer is highly reusable, it should be possible to integrate our proxy architecture in nearly any networked application with minimal effort. Network awareness on the other hand is gained by periodically measuring the latency, throughput and packet loss rate of the network links going to the clients currently connected to the proxy. Furthermore, each proxy records the bandwidth usage of every data stream that passes through it.

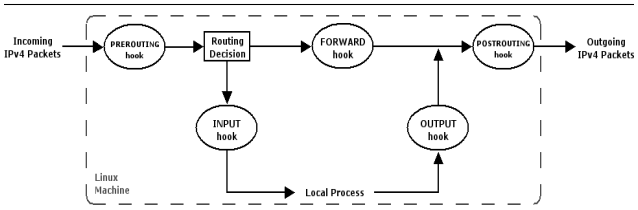



**Figure 2. IPv4 packet traversal diagram.**

Our proxies continuously combine their application and network awareness to devise a strategy for every connected client that intelligently distributes the client's available bandwidth over the different streams present in the system. For example, when a client's available downstream bandwidth no longer suffices to receive all streams at maximum quality, the proxy will determine which streams should be reduced in quality or even completely blocked. This decision will be based on the relative importance of the streams as well as their bandwidth requirements. As a result, whenever possible, less important streams will be transcoded or dropped by the proxy before more significant streams are altered, this way maximizing the user QoE. The algorithm used to compute the bandwidth allocation strategies is described in [11].

To implement the proxy's packet filtering, routing and mangling functionality, we used the netfilter/iptables framework [19] which is part of the Linux kernel since version 2.4. Netfilter defines a set of *hooks* for a number of network stacks (for example, the five hooks defined for IPv4 are illustrated in figure 2) and allows kernel modules to register callback functions for these hooks. Whenever a packet arrives at a hook, netfilter checks if anyone has registered a callback function for it. If this is the case, the packet is transferred from the network stack to this callback function, which can then examine the packet and subsequently decide on its fate. Iptables on the other hand enables packet selection in userspace. More specifically, iptables allows users to

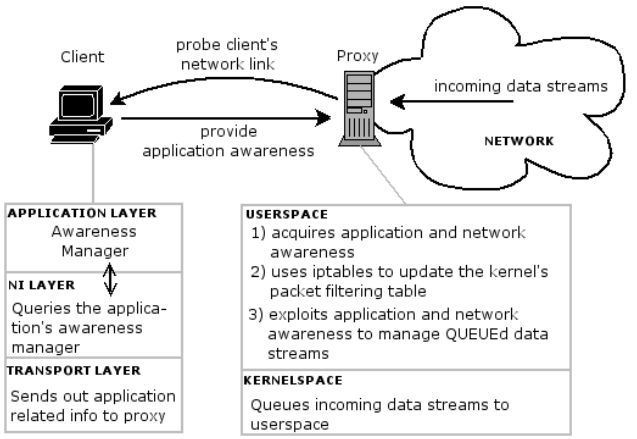



**Figure 3. High-level overview of the operation of our application and network aware proxy.**

insert and delete rules from the kernel's packet filtering table for any of the hooks defined by netfilter. A rule specifies what should be done with a packet if its header matches the conditions specified in the rule. Possible verdicts a rule can issue for a packet include ACCEPT (let the packet pass), DROP (discard the packet) and QUEUE (hand the packet over to a userspace application which can then decide what should be done with the packet). If a packet does not match the conditions of the current rule, the next rule for that hook is consulted.

Iptables is used by our proxies to do some trivial packet filtering directly (e.g. always issue an ACCEPT verdict for network probes), and to QUEUE packets belonging to data streams of the served application to a userspace program [21]. Possible data streams in networked multi-user applications include audio, video, geometry, and position and orientation updates. The userspace application subsequently consults the computed bandwidth allocation strategy for the client this stream applies to, and leverages this information to decide if the packet should be accepted, dropped or transcoded. This means both the proxy's application and network awareness is exploited when managing and controlling application data streams. This approach leads to an improved QoE for application users, as will be demonstrated in section 5. A schematic overview of the general mode of operation of our proxies is shown in figure 3.

### 3.2. Video transcoding plug-in

To achieve maximal usability, we have tried to keep our proxies as generic as possible. As a result, the proxy can by default execute only a limited number of basic operations on data streams. For example, the standard version of the proxy is capable of performing Network Address Translation (NAT), but has otherwise no additional packet mangling functionality. However, we have equipped our proxies with a plug-in mechanism which can be used to extend their performance and capabilities. Application designers can write their own plug-in that exploits specific knowledge of their application and suits their specific needs, and install it in the proxy. This approach ensures that our proxies can be integrated in nearly all networked applications and attain a high level of performance in all these situations.

The plug-in we used in [21] to validate our work was a simple quality selection plug-in capable of turning data streams on and off. Even though this plug-in worked fine, we felt there was a need for a more fine-grained stream management plug-in. Therefore, we have developed a new plug-in capable of transcoding video streams in real-time. We used FFMPEG's codec library libavcodec [18] to implement this functionality. Libavcodec contains encoders and decoders for nearly all prevailing video standards, like for example H.263 [5] and MPEG-4 [4]. The developed plug-in dynamically spawns and destroys transcoders for any of the video streams present in the application as they become needed/obsolete. Since transcoding performance was not one of our main objectives, we opted to implement these transcoders using the cascaded pixel-domain approach. In this approach, a video stream is transcoded by first decoding it and subsequently completely re-encoding it with different quality parameters. While this approach is hardly efficient, it produces the best results in terms of image quality of all existing video transcoding architectures [20].

## 4. Sample NVE application

We tested our work by integrating it into our in-house developed multi-user NVE framework which was first introduced in [14]. The primary objective of this framework is to attain scalability, both in terms of number of simultaneous users as well as spatial extent of the offered virtual environment. The framework tries to achieve this goal by maximizing client responsibilities and relying extensively on direct client-to-client multicast communication. In a later stage, the framework was extended with support for *video-based avatars*, a technique in which the face of a user is continuously captured with a webcam and subsequently textured on his avatar [13]. The objective here was to increase the immersive experience for connected users. Figure 4 shows two screenshots of the NVE framework running on desktop PCs.

The standard version of the framework divides the virtual environment into square regions which each have a unique multicast address associated with them. Whenever something happens in the virtual world, information about the event is sent only to the multicast address of the region from

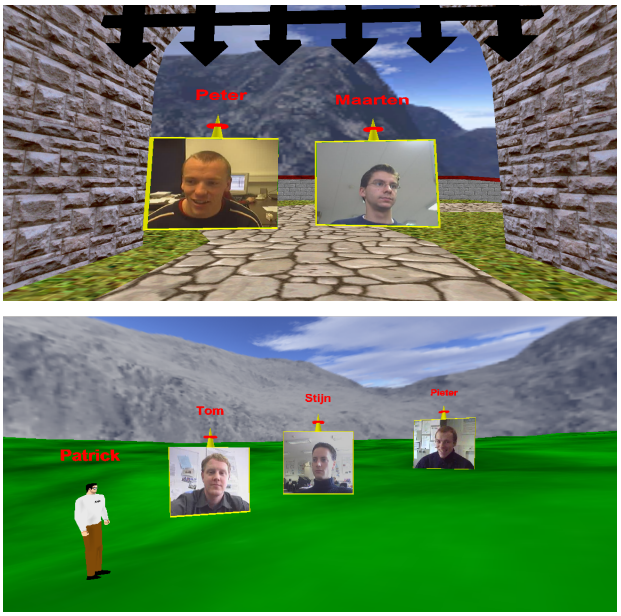



**Figure 4. Two screenshots of our in-house developed multi-user NVE framework supporting video-based avatars.**

| | High Quality (HQ) | Medium Quality (MQ) | Low Quality (LQ) |
|---|---|---|---|
| Codec | H263 | H263 | H263 |
| Resolution | CIF (352x288) | CIF (352x288) | CIF (352x288) |
| FPS | 25 | 15 | 15 |
| Bitrate (bps) | 200.000 | 100.000 | 50.000 |

**Table 1. Quality settings of the three video streams video-based clients send out.**

which the event originated. Each client has an Area of Interest (AoI) manager that is responsible for constantly determining the regions this user should be aware of. As the user moves around the world, the multicast groups associated with the regions selected by the AoI manager are dynamically joined and left, this way limiting the amount of information clients need to receive and process. However, the framework also divides the world into video regions. Each user represented by a video-based avatar in the virtual world sends out three distinct qualities (high, medium and low) of his video stream, one to each of the three multicast addresses associated with the video region he is currently located in. Table 1 shows the different quality parameters the framework utilizes to encode the three versions of a user's video stream. Like the AoI manager, the Video Area of Interest (VAoI) manager decides which video multicast addresses the client should subscribe to. One strategy could be to subscribe to the high quality multicast group of the video region the user currently is in, and to the medium or even low quality groups of adjacent video regions.

## 5. Experimental results

A detailed discussion of the integration of our proxy system into the multi-user framework described in the previous section can be found in [21]. However, the results presented in that paper were obtained by using a simple video quality selection plug-in for our proxies. This plug-in exploited the proxy's application and network awareness to improve the QoE for connected users by determining which quality (if any) they should receive from every video-based avatar in the virtual world. Based on the decisions taken by the plug-in, the proxy subsequently dropped certain video qualities before they reached the user. Note that since we position our intelligent proxies close to end-users, the complexity of stream management is moved to the edge of the network where the number of streams is relatively low.

Although the quality selection plug-in worked fine, users represented by video-based avatars were still required to send out three distinct qualities of their video stream. This requirement places an extra load on the processor of the client device, since the user's video stream needs to be encoded three separate times. More importantly however, this approach also requires a large amount of client upstream bandwidth. Most Internet Service Providers (ISPs) provide asymmetric Internet subscriptions in which the upstream capacity is merely a fraction of the offered downstream bandwidth (typically 128 or 192 Kbps). As a result, forcing clients to send out three different qualities of the same video stream is something commercial applications just cannot afford at the moment. By equipping our proxy system with transcoding functionality, we can relieve framework clients from this burden. After slightly modifying the general transcoding plug-in described in section 3, we obtained the plug-in shown in figure 5. This plug-in intercepts high quality encoded video streams (which are now the only video streams clients need to send out), transcodes them to medium and low quality versions if at least one of the proxy's connected clients is interested in that quality, and subsequently serves every client the appropriate version.

To assess the value our new plug-in adds to the framework, we performed an experiment which involved four clients running the unmodified version of the framework (clients C1 to C4 in figure 6(a)) and two clients connected through our transcoding-enabled proxy (clients PA and PB in figure 6(a)). Only clients C1, C2 and C3 were represented as video-based avatars. During the experiment, we artificially varied the available downstream bandwidth of clients

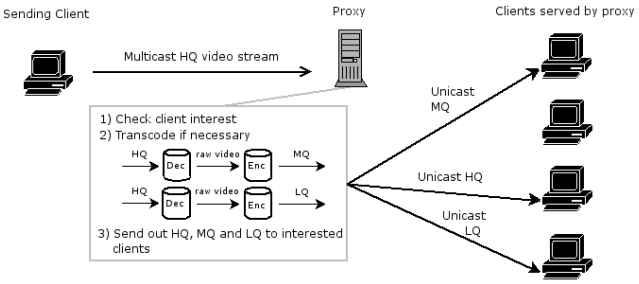
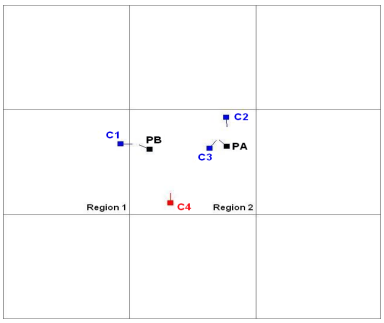



**Figure 5. High-level operation of the video transcoding plug-in.**

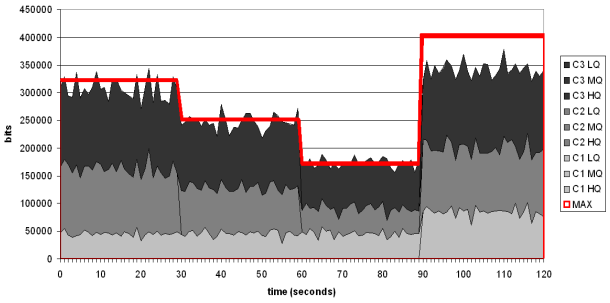
PA and PB over time, while all other clients remained stationary in the virtual world. Notice that since in this experiment the virtual world was inhabited by both standard as well as proxy-enhanced clients, the video-based clients still needed to send out three distinct video qualities. If however the world would have been populated solely by clients connected through our intelligent proxy (which is actually the scenario we envision), it would have sufficed for video-based clients to only send out the high quality encoded version of their video stream.

At the beginning of the experiment, we set the bandwidth of clients PA and PB to 320 Kbps. Due to its network awareness, the proxy noticed this bandwidth did not suffice for PA and PB to receive the high quality video streams of all three video-based avatars. As a result, our proxy exploited its application awareness to transcode certain video streams to medium or low quality, and subsequently transmitted these transcoded versions to its clients instead of their high quality counterparts. After 30 seconds, we limited PA's and PB's bandwidth to 250 Kbps, and after 60 seconds we further decreased their bandwidth to 170 Kbps. Finally, after 90 seconds, we increased the downstream bandwidth of PA and PB back to 400 Kbps.

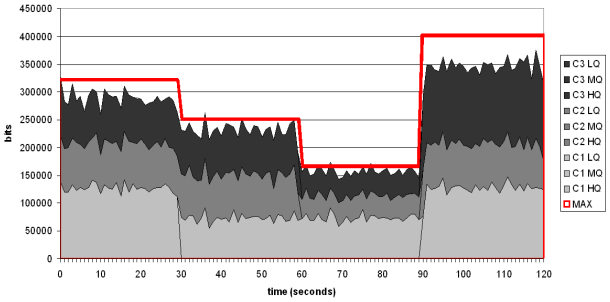
Figures 6(b) and 6(c) show all video network traffic received by respectively client PA and client PB. A first important observation is that PA and PB both roughly stayed within their bandwidth limitations for the entire duration of the experiment. Secondly, these network traces also clearly indicate how our proxy exploits its application awareness to intelligently decide which video streams should be transcoded to a lower quality in case of insufficient client bandwidth. For example, since the distance between PA and C1 was much larger than the distance between PA and C2 and C3, the proxy allocated most of PA's available bandwidth to the video streams sent out by C2 and C3 (see figure 6(b)). On the other hand, since PB was located very close to C1 in the virtual world, the majority of PB's downstream bandwidth was allocated to C1's



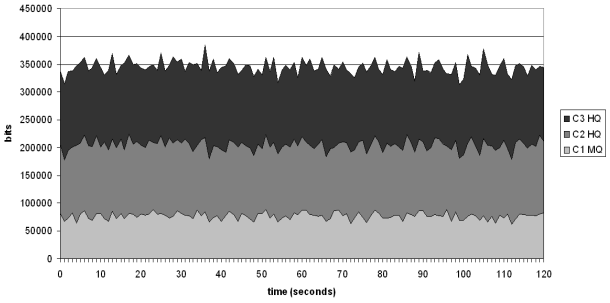

(a) Client positioning in the virtual world.




(b) Video packets received by client PA.




(c) Video packets received by client PB.




(d) Video packets received by client C4.

**Figure 6. Network traces (stacked graphs) of an experiment in which we artificially varied the downstream bandwidth clients had at their disposal over time.**

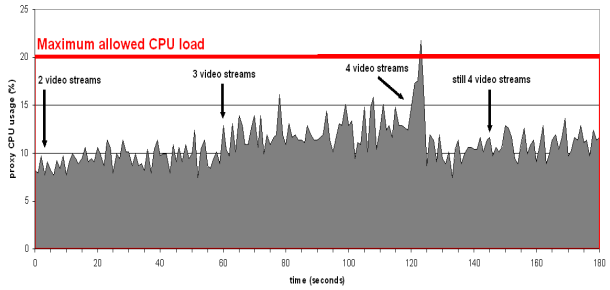



**Figure 7. The transcoding plug-in is equipped with an intelligent scaling mechanism to maximize the number of clients our proxies can handle simultaneously.**

video stream (see figure 6(c)). In contrast, figure 6(d) illustrates all video packets received by client C4. Since this client was not connected through a transcoding-enabled proxy, its VAoI manager was responsible for performing video quality selection. Unlike our proxy however, the VAoI manager lacks network awareness. As a result, client C4 received the same set of video streams during the entire experiment. If this client would have been subject to the same bandwidth fluctuations as clients PA and PB, its bandwidth would have been exceeded numerous times since no attempts would have been made to adjust the bandwidth usage of individual video streams. Exceeded client downstream bandwidth results in increased packet loss and higher video packet delay, which seriously deteriorates the video playback and consequently also the user's immersive experience.

By comparing the network traces in figures 6(b) and 6(c) with the one in figure 6(d), the added value of our work becomes clear. Our transcoding-enabled proxy at all times exploits all available client bandwidth without ever exceeding it, and intelligently and dynamically distributes this bandwidth over all involved network streams in order to optimize the user QoE. Unsurprisingly, these results are almost identical to those presented in [21]. However, as stated before, scarce upstream bandwidth is no longer wasted since clients normally no longer need to send out different qualities of the same video stream. Furthermore, these results also illustrate the flexibility of our proxy system. By simply installing a new plug-in, the functionality of our proxy system was extended with transcoding capabilities.

A drawback of the new plug-in is its computational complexity. As stated before, video transcoding is very processor intensive, with the cascaded pixel-domain approach being the least efficient of all transcoding architectures. As a result, the transcoding plug-in is much less scalable than the previously developed quality selection plug-in. Although transcoding performance was not one of our main objectives, we nonetheless wanted the number of clients our proxy could support simultaneously to be as high as possible. We therefore incorporated an intelligent scaling mechanism in the transcoding plug-in. If over a short time interval the proxy's average processor usage exceeds a predefined threshold, medium quality transcoding is disabled for all video streams and clients are served the low quality version instead. This has two advantages. First of all, low quality encoding is slightly less processor intensive than medium quality encoding. Secondly, by disabling medium quality encoding, transcode results can be reused to a higher degree. For example, suppose two clients are connected to the same proxy, with one client being interested in the medium quality of a certain video stream while the other is interested in the low quality version. If the proxy has sufficient processor time available, it transcodes the high quality video stream to medium as well as low quality and serves both clients the quality they prefer. However, if the proxy's threshold is exceeded, only low quality transcoding is enabled and both clients will consequently receive the low quality version of the video stream, resulting in a decrease in processor load by a factor of two approximately. This is illustrated in figure 7. Here, the threshold was set to an unusually low 20 percent processor usage for testing purposes only. Normally, the threshold value would be much higher, like for instance 80 or 90 percent processor load.

## 6. Conclusions and future work

In this paper, we have described the implementation of a video transcoding plug-in for our generic proxy system. Furthermore, we have also presented results from integrating our transcoding-enabled proxies in an existing NVE framework. These results are very similar to those achieved by a previously developed quality selection plug-in. More specifically, both plug-ins can equally improve the user QoE in networked multimedia applications. However, the transcoding plug-in relieves client machines from having to send multiple versions of the same video stream. We believe this to be an interesting advantage due to the asymmetric nature of most current Internet subscriptions. On the other hand, since transcoding is computationally expensive, the transcoding plug-in is less scalable than the quality selection plug-in. We have therefore equipped the transcoding plug-in with an intelligent scaling mechanism to push the number of clients our proxies can handle simultaneously to the limit. Finally, the results presented in this paper also clearly illustrate the flexibility of our generic proxy system. By simply installing a new plug-in, transcoding functionality was added to our proxies. By implementing and installing other novel plug-ins, their capabilities and range of application could easily be extended even further.

In the future we would like to improve our work in several ways. First and foremost, our intelligent proxy system at the moment still lacks device awareness. We envision the proxy gathering information regarding the capabilities of the receiving client device and combining this knowledge with its application and network awareness to take more complex transcoding decisions and to distribute the bandwidth of clients even more efficiently. Secondly, we would like to perform some more elaborate experiments, for instance by including mobile devices. Finally, we will keep looking at ways to increase the performance and scalability of our transcoding plug-in.

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## References

[1] E. Amir, S. McCanne, and H. Zhang. An Application Level Video Gateway. In *Proc. 3rd ACM International Conference on Multimedia*, pages 255–265, San Francisco, California, November 1995.

[2] D. Bauer, S. Rooney, and P. Scotton. Network Infrastructure for Massively Distributed Games. In *Proc. 1st Workshop on Network and System Support for Games (NetGames'02)*, pages 36–43, Bruanschweig, Germany, 2002. ACM Press.

[3] E. Cronin, B. Filstrup, and A. Kurc. A Distributed Multiplayer Game Server System. UM Course Project Report EECS589, Electrical Engineering and Computer Science Department, University of Michigan, May 2001.

[4] ISO/IEC 14496 (MPEG-4). Coding of Audio-Visual Objects. ISO/IEC JTC1, 2001.

[5] ITU-T Recommendation H.263. Video Coding for Low Bit Rate Communication. 1998.

[6] B. Knutsson, H. Lu, J. Mogul, and B. Hopkins. Architecture and Performance of Server-Directed Transcoding. *ACM Transactions on Internet Technology*, 3(4):392–424, 2003.

[7] Z. Lei and N. Georganas. Video Transcoding Gateway for Wireless Video Access. In *Proc. IEEE Canadian Conference on Electrical and Computing Engineering (CCECE'03)*, Montreal, May 2003.

[8] C.-Y. Lin, A. Natsev, B. Tseng, M. Hill, and J. Smith. Pervasive Transcoding Middleware for Geospatial Intelligence Access. In *Proc. IEEE International Conference on Multimedia & Expo (ICME'04)*, Taipei, Taiwan, June 2004.

[9] A. Maheshwari, A. Sharma, K. Ramamritham, and P. Shenoy. TranSquid: Transcoding and Caching Proxy for Heterogenous E-Commerce Environments. In *Proc. 12th IEEE International Workshop on Research Issues in Data Engineering (RIDE'02)*, pages 50–59, San Jose, California, February 2002.

[10] M. Mauve, S. Fischer, and J. Widmer. A Generic Proxy System for Networked Computer Games. In *Proc. 1st Workshop on Network and System Support for Games (NetGames'02)*, pages 25–28, Bruanschweig, Germany, 2002. ACM Press.

[11] P. Monsieurs, M. Wijnants, and W. Lamotte. Client-controlled QoS Management in Networked Virtual Environments. In *Proc. 4th International Conference on Networking (ICN'05)*, pages 268–276, Reunion Island, April 2005.

[12] C. D. Nguyen, F. Safaei, and P. Boustead. A Distributed Proxy System for Provisioning Immersive Audio Communication to Massively Multi-Player Games. In *Proc. 3rd Workshop on Network and System Support for Games (NetGames'04)*, page 166, Portland, Oregon, USA, September 2004. ACM Press.

[13] P. Quax, C. Flerackers, T. Jehaes, and W. Lamotte. Scalable Transmission of Avatar Video Streams in Virtual Environments. In *Proc. IEEE International Conference on Multimedia & Expo (ICME'04)*, Taipei, Taiwan, June 2004.

[14] P. Quax, T. Jehaes, P. Jorissen, and W. Lamotte. A Multi-User Framework Supporting Video-Based Avatars. In *Proc. 2nd workshop on Network and System Support for Games (NetGames'03)*, pages 137–147, Redwood City, California, May 2003. ACM Press.

[15] B. Shen, S.-J. Lee, and S. Basu. Performance Evaluation of Transcoding-enabled Streaming Media Caching System. In *Proc. 4th International Conference on Mobile Data Management*, pages 363–368, Melbourne, Australia, January 2003.

[16] B. Shen, S.-J. Lee, and S. Basu. Caching Strategies in Transcoding-enabled Proxy Systems for Streaming Media Distribution Networks. *IEEE Transactions on Multimedia, Special Issue on Streaming Media*, 6(2):375–386, April 2004.

[17] J. Smith, R. Mohan, and C.-S. Li. Content-Based Transcoding of Images in the Internet. In *Proc. IEEE International Conference on Image Processing (ICIP'98)*, volume 3, pages 7–11, Chicago, Illinois, 1998.

[18] The FFMPEG Homepage. World Wide Web, `http://www.ffmpeg.org`.

[19] The Netfilter/IPTables Project Homepage. World Wide Web, `http://www.netfilter.org`.

[20] A. Vetro, C. Christopoulos, and H. Sun. Video Transcoding Architectures and Techniques: An Overview. *IEEE Signal Processing Magazine*, 20(2):18–29, March 2003.

[21] M. Wijnants, P. Monsieurs, and W. Lamotte. Improving the User Quality of Experience by Incorporating Intelligent Proxies in the Network. Technical Report TR-LUC-EDM-0605, Expertise Centre for Digital Media (EDM), April 2005, `http://research.edm.luc.ac.be/~mwijnants/pdf/wijnantsTRMSAN.pdf`.

[22] X. Zhang, M. Bradshaw, Y. Guo, B. Wang, J. Kurose, P. Shenoy, and D. Towsley. AMPS: A Flexible, Scalable Proxy Testbed for Implementing Streaming Services. In *Proc. 14th International Workshop on Network and Operating System Support for Digital Audio and Video (NOSSDAV'04)*, pages 116–121, Kinsale, Ireland, June 2004. ACM Press.