QoE- and Energy-aware Content Consumption For HTTP Adaptive Streaming

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ABSTRACT

Video streaming services account for the majority of today's traffic on the Internet, and according to recent studies, this share is expected to continue growing. Given this broad utilization, research in video streaming is recently moving towards energy-aware approaches, which aim at reducing the energy consumption of the devices involved in the streaming process. On the other side, the perception of quality delivered to the user plays an important role, and the advent of *HTTP Adaptive Streaming* (HAS) changed the way quality is perceived. The focus is not any more exclusively on the Quality of Service (*QoS*) but rather oriented towards the Quality of Experience (*QoE*) of the user taking part in the streaming session. Therefore video streaming services need to develop Adaptive BitRate (ABR) techniques to deal with different network conditions on the client side or appropriate end-to-end strategies to provide high QoE to the users. The scope of this doctoral study is within the end-to-end environment with a focus on the end-users domain, referred to as the player environment, including video content consumption and interactivity. This thesis aims to investigate and develop different techniques to increase the delivered QoE to the users and minimize the energy consumption of the end devices in HAS context. We present four main research questions to target the related challenges in the domain of content consumption for HAS systems.

CCS CONCEPTS

• **Networks** → **Application layer protocols**; • **Information systems** → **Multimedia streaming**; • **Computing methodologies** → *Machine learning*.

KEYWORDS

Multi-codec, HTTP/3, machine learning, green computing, HAS

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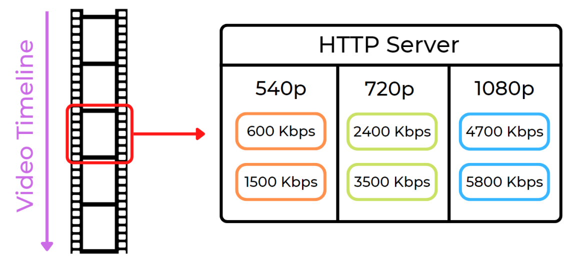

Figure 1: Example of HAS: for each non-overlapping video segment (red box) different representations are generated.

1 INTRODUCTION

Video streaming is the most important service in telecommunication networks. According to the estimations provided in the *Ericsson Mobility Report* [10], video streaming accounted for 69% of all mobile data traffic at the end of 2021, and it is forecast to reach 79% in 2027. Based on these statistics, video streaming service providers demand new techniques to provide high quality to their customers.

The considered quality refers not only to the intrinsic video quality (*e.g.*, PSNR, VMAF, *etc.*) but also to the Quality of Experience (*QoE*) of the user, *i.e.*, the user's satisfaction while watching the video. Different from the Quality of Service (*QoS*), *i.e.*, based on technical metrics mainly related to the network performance, this change in quality perspective coincides with the advent of *HTTP Adaptive Streaming* (HAS). In HAS – including *Dynamic Adaptive Streaming over HTTP* (DASH) [7] and *HTTP Live Streaming* (HLS) [21] – a video content stored at the server is encoded at several quality versions, each identified by a specific bitrate. Each version is then temporally divided into segments of the same duration. This process generates a fixed number of segments for each quality *representation* of the video. An illustrative example is shown in Fig. 1. When the video segments are generated and available, the client sends HTTP requests to fetch them sequentially.

Based on the network conditions, the Adaptive BitRate (ABR) algorithm implemented at the player selects the most suitable representation. ABR algorithms can be organized into four classes [2], including (i) *client-based*, (ii) *server-based*, (iii) *network-assisted*, (iv) *mixed adaptation*.

The majority of the existing ABR algorithms [12, 19, 25] focus on three main objectives: (i) maximizing the bitrate, (ii) minimizing the number of stalling events due to an empty client buffer, and (iii) minimizing the oscillations in bitrate selections. However, since the bitrate does not map directly to the quality perceived by users, the state-of-the-art models for QoE estimation adopted in the literature have limited accuracy [31].

Although the relationship between bitrate and quality can be modeled as a logarithmic function, this approximation lacks context, which is the complexity of the content. The use of perceptual quality metrics, such as Video Multi-Method Assessment Fusion (VMAF), helps to understand the relationship between video bitrate and perceived quality. Trading off between bitrate and quality is essential because decreasing the bitrate can reduce energy consumption on the end device. Hence, with video streaming accounting for a large portion of the Internet data traffic and many end devices being employed in the process, there is a need for a technique to reduce the energy consumption of both streaming and playback processes. We first plan to investigate the importance of the main factors contributing to energy consumption in player systems, such as bitrate, resolution, content complexity, codec, and screen brightness. Based on the results, we aim to develop an approach to reduce the energy consumption of end devices without sacrificing the QoE of the users.

Upcoming protocols and technologies (*i.e.*, HTTP/3, QUIC, *etc.*) can also help in improving the QoE of the users. HTTP/3 [4] and QUIC [11] protocols can support ABR algorithms with features such as *stream multiplexing*, *stream priority*, and *stream termination*, and *server push*, which enable the client to download segments concurrently, assign priority weights, terminate streams and receive multiple segments with a single request, respectively. Currently, the main issue is how to combine these features. Therefore, we plan to analyze their impact on video streaming and, based on these findings, develop an approach to combine these features to increase the QoE of the users.

From the content provisioning point of view, QoE is linked to the quality of the encoded video. AVC (Advanced Video Coding) [34] is currently the video codec most supported by the existing streaming platforms (*e.g.*, Netflix, Youtube), but due to its low compression efficiency new generation video codecs, e.g., HEVC (High Efficiency Video Coding) [27], VP9 (Video Processor 9) [17], AV1 (AOMedia Video 1) [6] and VVC [5], have been developed. The browsers and video streaming platforms available in the market support specific sets of video codecs [16]. In a streaming session with multiple available codecs, the decision on which codec to request is often based on compression efficiency and delegated to the client. However, this approach is static and does not consider content complexity, and in some cases, AVC can achieve the same or higher compression efficiency as HEVC [3]. Therefore, we plan to analyze the compression efficiency of several video codecs depending on the processed video to estimate valuable properties of the output content, such as quality and segment sizes. Based on these findings, we aim to develop a strategy for the dynamic codec selection to improve the QoE of the end user given the constraints of such systems (*e.g.*, supported codecs, throughput) and additional metadata, like browsers statistics, quality metrics, and segment sizes.

High-quality videos can be requested when network throughput is abundant, resulting in the highest possible QoE. However, if the throughput drops, low-quality videos may be fetched to avoid stall events, negatively impacting QoE. Recent machine learning techniques, such as super-resolution, denoising, and deblocking [13, 23, 29], can enhance low-quality videos by restoring fine frame features or details. While these techniques have mainly been applied to images, their application in video streaming is a recent topic. Therefore, we aim to investigate the properties of machine learning tools in the context of HAS to develop client-side techniques for increasing QoE.

Given the above-mentioned issues, the objective of this thesis is to provide insightful analysis and specific artifacts in the context of HAS on one side to increase the delivered QoE to the users and on the other, where possible, to reduce the energy consumption of the devices involved in the streaming process.

2 RESEARCH QUESTIONS

After reviewing the literature of our research field, we investigate the following research questions:

(1) **How to exploit features of emerging/future networking paradigms for improving the QoE of end users in HAS?**
Emerging/future networking paradigms and protocols (*e.g.*, HTTP/3, QUIC) bring in new features (*e.g.*, 0-RTT for connection establishment, stream multiplexing, stream priority, stream termination) that provide several improvements in the network performance metrics (*e.g.*, latency, head-of-line blocking, RTT). We want to integrate the considered networking paradigms and protocols in HAS and exploit the provided features to improve the QoE of the end users.

(2) **How to efficiently deliver video representations encoded with multiple codecs for increasing the QoE of the end user in HAS?**
When a video sequence is available for streaming in multiple codecs, the player must decide which one to request at the beginning of the streaming session. This decision is based on general compression efficiency estimations and platform support. However, it lacks dynamicity since the codec, once chosen, does not change throughout the reproduction. Furthermore, this naive approach does not consider content complexity. According to specific video contents and within appropriate bitrate ranges, an old-generation codec, like AVC, can provide higher compression efficiency than a new-generation one, like HEVC. Therefore, we aim to devise an ABR technique to enable dynamic switching across codecs efficiently. The client can make this decision based on video metadata, like quality and segment size, and context statistics, such as the codecs supported by the player and their overall percentage of adoption.

(3) **How to devise energy-aware ABR techniques to jointly increase the QoE of the end user and reduce the energy consumption in HAS systems?**
With the recent increase in data traffic associated with video streaming over the Internet, a serious question arises about the energy consumption of the devices involved in video streaming. Most studies on ABR techniques focus on well-known metrics, such as average bitrate, stalls, and video instability. However, although generally valid, the assumption of a universal logarithmic relationship between bitrate and

video quality lacks specificity since this function depends on the video content. In practice, the quality improvement followed by a bitrate increase is visually noticeable up to a certain threshold. From an end-user perspective, the further we proceed over this threshold, the higher the waste of data and energy that fetching and decoding such content will generate. To enable energy-aware streaming, we plan to devise ABR techniques to reduce the energy consumption of end devices without sacrificing the QoE of the user.

(4) **How to exploit machine learning techniques at the client side to enhance video content and improve the QoE of the end user in HAS?**
Machine Learning (ML) techniques to enhance video content have already become state-of-the-art. What made this possible were not only the recent improvements in techniques such as image restoration (*i.e.*, super-resolution, denoising, and deblocking) and frame interpolation but also the increase in processing capabilities of consumer-grade devices. Although many techniques have been recently developed for video content, only a few studies focus on their implications on ABR video streaming. In this context, ML brings several benefits, like bandwidth reduction or quality enhancement, as compressed or down-scaled videos can be reconstructed after being received on the client side. Furthermore, ML can be applied to increase the video frame rate through interpolation between temporal-adjacent frames. Assuming the expected enhancements in the video content, we plan to integrate novel ML techniques on the client side to analyze their effects on the overall QoE of the end users.

3 RELATED WORK

There have been some attempts to answer the aforementioned research questions in the literature:

RQ-1 The existing *client-based* ABR algorithms can be classified into four groups [2]: (i) *throughput-based*, (ii) *buffer-based*, (iii) *hybrid-based*, (iv) *Markov Decision Process (MDP)-based*. Although they provide relevant policies to cope with bandwidth fluctuation, the majority of the available ABR approaches are unaware of the underlying web technologies and protocols, such as HTTP/3 and QUIC. However, with this knowledge, appropriate features can be exploited to improve the performance of these techniques.
Several publications focus on the support of HTTP/3 [4] to enhance the QoE of video streaming [24, 30]. Timmerer *et al.* [30] investigate Dynamic Adaptive Streaming over HTTP (DASH) [26] performance over QUIC (v19). Furthermore, QUIC's (v39) behavior for HAS has been analyzed and compared with TCP's behaviour [24]. In these works, however, QUIC and HTTP/3 are evaluated in the default mode only, and no key features are exploited. Minh *et al.* [20] introduce an ABR technique to upgrade the low-quality buffered segments by retransmitting them at a higher quality exploiting HTTP/2's features. Although this work provides relevant insights into the use of HTTP's features, studies on QUIC and HTTP/3 are still needed.

RQ-2 Recently, the attention on multi-codec systems has been intensified, focusing prevalently on performance comparison, bitrate ladder optimization, and dataset generation [22, 28, 35]. Bienik *et al.* [35] compare the performance of AVC, HEVC, VP9, and AV1 based on video contents with different spatial (SI) and temporal information (TI). Reznik *et al.* [22] investigate the problem of creating an optimal multi-codec bitrate ladder based on network conditions and video content complexity and design an optimization strategy for the creation of such a bitrate ladder. Taraghi *et al.* [28] provide a multi-codec dataset comprising AVC, HEVC, VP9, and AV1 for DASH systems, enabling interoperability testing and streaming experiments for the efficient usage of these codecs under various conditions. Yet, on the client side, applications, such as ABR techniques or optimization models for efficient multi-codec delivery, still need to be developed.

RQ-3 In the context of video streaming, the attention to the energy consumption of end-user devices has recently increased. A direct consequence is the development of several energy-aware techniques [32, 33]. Varghese *et al.* [33] propose an energy-aware plugin for DASH players (eDASH) running on mobile devices to reduce the battery consumption of the device. The eDASH player considers bitrate and video brightness to determine the next chunk to download. Uitto *et al.* [32] use HEVC for video encoding to achieve similar qualities compared to other codecs while causing less power and data consumption. However, because of the low number of representations, these techniques fail to resemble real video streaming conditions. Furthermore, the impact of important metadata, such as file size, motion rate, and resolution, on the energy consumption is not investigated.

RQ-4 Several ML-based enhancement techniques have recently been applied to improve the visual quality of video content [1, 18, 23]. Stable Diffusion [23] exploits a latent diffusion model architecture for both text-to-image generation, in-paint modification, and super-resolution. Although it provides realistic results in significantly less time than normal diffusion models, the running time and computational requirements are still problematic for its implementation in mobile devices. Furthermore, a neural network with group convolutions has been proposed to increase super-resolution accuracy while decreasing computational costs over compared state-of-the-art approaches [1]. Other works focus on super-resolution applied to HAS [18]. SR-WISH [18] is a lightweight framework including a CNN and an ABR algorithm to apply super-resolution only under certain conditions, defined by the ABR algorithm based on a multi-objective function. Despite video enhancement referring to a large number of applications, super-resolution is lately the main focus of researchers. Therefore, further work on topics, such as frame interpolation, video deblocking, and video denoising, in the context of HAS is still needed.

4 METHODOLOGY

For the purpose of addressing the research questions mentioned above, we are going to follow the *design* paradigm, which is rooted in engineering and introduced by P.J. Denning *et al.* [8]. This methodology includes (1) *developing a solution*, (2) *implementing the prototype software*, (3) *analyzing the system quantitatively and qualitatively*, and (4) *refining the solution* by repeating the cycle.

These steps are iterated until the system satisfactorily meets the requirements declared in the first step.

In the first step, it is crucial to define all the requirements the proposed solution must meet. For instance, in the case of an algorithm, it might regard execution time, accuracy, scalability, or other custom metrics. After the solution proposal, the implementation follows. This step is essential to obtain an executable or analyzable system. Once the prototype is ready, it is profoundly evaluated, and the relevant properties and metrics are gathered. At this point, the process can stop if the conditions defined in the first step are satisfied. Otherwise, it is wise to restart from the first step and refine the solution.

This methodology has been adopted for all the publications presented in Sec. 5 and will be further employed for ongoing and future work.

5 PUBLICATIONS AND FUTURE WORK

To address RQ-1, a study has been conducted on the advantages of HTTP/3 and QUIC features in novel ABR strategies and published in the IEEE Access journal [19]. Based on this study, we propose a novel ABR algorithm, namely Days of Future Past Plus (DoFP+), which follows our previous work, termed Days of Future Past (DoFP) [14], published in the 3rd ACM CoNEXT 2021 Workshop on the Evolution, Performance, and Interoperability of QUIC (EPIQ). DoFP+ jointly selects the bitrate for the next (future) and low-quality buffered (past) segments based on a multi-objective function. Besides, it leverages some key features of HTTP/3 and QUIC features to download those segments efficiently. *Stream multiplexing* is exploited to fetch multiple segments simultaneously, and *stream priority* is enabled to define a download priority list based on our findings concerning the impact of segment qualities on the QoE. While redownloading buffered segments, if the throughput drops or the buffer is close to running out, DoFP+ will terminate those segments using the *stream termination* feature.

The results show that DoFP+ can significantly increase the QoE score by up to 33% while reducing video instability and stall events by up to 66% and 92%, respectively, compared to state-of-the-art approaches. Moreover, DoFP+ downloads more upgraded segments with higher quality than DoFP.

For RQ-2, we focus on the advantages that the availability of multiple codecs in the delivery phase could bring.

For this purpose, an optimization model termed MCOM-Live, *Multi-Codec Optimization Model at the edge for Live streaming*, has been developed [15]. For each considered segment timeline and a fixed multi-codec bitrate ladder, acting at the edge server, MCOM-Live selects the optimal policy, *i.e.*, *fetch*, *transcode*, or *skip*, to handle each representation based on a multi-objective function, considering fetching and transcoding cost, and video quality. Furthermore, we implemented the light-weight approach presented by Alireza *et al.* [9] to reduce the computational cost of transcoding tasks.

Based on our results, MCOM-Live can reduce serving time and streaming costs by up to 23% and 78%, and increase the PSNR by up to 0.5dB, based on the selected weights configuration.

This paper has been accepted for publication at the 29th International Conference on Multimedia Modeling (MMM).

To address RQ-3, we plan to investigate the importance of factors, such as video bitrate and resolution and screen brightness, contributing to energy consumption on the client side. With this knowledge, we plan to devise energy-aware ABR techniques deployed on the player to reduce the energy consumption of the end devices without sacrificing the QoE of the user. Moreover, the energy impact of relighting techniques for dark video content will be evaluated in comparison to increasing screen brightness, which is known to negatively affect energy consumption.

The problem originating from RQ-4 can be tackled from different perspectives. To enhance the QoE of the end users, we want to exploit image-based ML techniques, such as CNNs, to generate spatially- and temporally-consistent video frames. First, we plan to devise a client-based light-weight technique to enable fast frame-rate interpolation between adjacent frames. Then, we aim to develop a generative neural network to be deployed on the client to selectively enable super-resolution, denoising, or deblocking, depending on the input video and the device's screen and processing capabilities.

6 CONCLUSION

In this doctoral study, we target four research questions to improve video streaming content consumption on the client side from different perspectives, including energy-aware ABR techniques, emerging network paradigms, multi-codec delivery, and ML approaches. We propose different approaches for each research question that have led to published contributions and will lead to further research in the content consumption process. Furthermore, the publications, ongoing work, and future work are presented, providing an overall vision of our doctoral studies.

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