Video Coding Enhancements for HTTP Adaptive Streaming

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ABSTRACT

Rapid growth in multimedia streaming traffic over the Internet motivates the research and further investigation of the video coding performance of such services in terms of speed and *Quality of Experience* (QoE). *HTTP Adaptive Streaming* (HAS) is today's de-facto standard to deliver clients the highest possible video quality. In HAS, the same video content is encoded at multiple bitrates, resolutions, framerates, and coding formats called *representations*. This study aims to *(i)* provide fast and compression-efficient multi-bitrate, multi-resolution representations, *(ii)* provide fast and compression-efficient multi-codec representations, *(iii)* improve the encoding efficiency of *Video on Demand* (VoD) streaming using content-adaptive encoding optimizations, and *(iv)* provide encoding schemes with optimizations *per-title* for live streaming applications to decrease the storage or delivery costs or/and increase QoE.

CCS CONCEPTS

• **Information systems → Information systems applications**; • **Multimedia information systems** → *Multimedia streaming*.

KEYWORDS

Adaptive Streaming; Multi-encoding; Content-adaptive Encoding; Per-title Encoding; Live Streaming.

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1 INTRODUCTION

Motivation: Over 66% of mobile data traffic in 2020 was video content which is expected to increase to 77% by 2026[1]. This increase in video traffic and improvements in video characteristics such as resolution, framerate, and bit-depth raises the need to develop a large-scale, highly efficient video encoding environment [7]. Since *Over-the-top* (OTT) video services such as Netflix, YouTube, and Disney+ are delivered as best-effort services, *HTTP Adaptive Streaming* (HAS) has become the *de-facto* standard for providing videos over the Internet [3]. In HAS, a video sequence is segmented into smaller *chunks* encoded at multiple bitrates, resolutions, framerates, and coding formats called *representations*. The client then downloads the video chunks and continuously re-evaluates which representation offers the best *Quality of Experience* (QoE) and is sustainable under the given network conditions [33].

A video can be intuitively represented as a series of images (frames). Since the adjacent frames are similar to each other, techniques to exploit the temporal correlation along with the traditional image coding techniques are employed in video coding, which further compress the video without much information loss. The new generation video codecs improve the coding efficiency with an additional overhead of increased computational complexity. One of the recent popular video codecs, *High Efficiency Video Coding* (HEVC) [34] improves the coding efficiency by up to 50% to maintain the same objective visual quality compared to its predecessor, *Advanced Video Coding* (AVC) [36] [26]. Moreover, a recently developed video codec, *Versatile Video Coding* (VVC) [6] claims to improve the coding efficiency further using more sophisticated encoding tools at the cost of an overall increase in the computational complexity of the encoding process[2]. The encoding time has increased by about 2000% from AVC to HEVC and 954% from HEVC to VVC coding standard [26]. As more consumer devices supporting different coding formats are introduced, it is essential to implement a *multi-codec* approach to address as much of the target audience as possible [37]. Encoding video content in more than one codec is costly as more investment in terms of processing power is needed[3].

Per-title encoding has gained attraction over recent years in HAS applications [7]. Per-title refers to the entire "title," in the sense of the whole film or TV show, or video sequence. Per-title encoding is based on the fact that different types of video content require different bitrates and encoding settings to achieve a certain quality. Each video is segmented into multiple shots; each shot is downscaled to a set of spatial resolutions. All are encoded at a set of bitrates while their quality is compared to the original shot. A *convex-hull* is formed based on these quality measures, and the optimal resolution is selected for each bitrate for each shot. Since the brute-force approach to determining the convex-hull is computationally intensive, it calls for fast convex-hull prediction schemes for content-adaptive compression in best-effort video streaming services.

Target: The goal of this doctoral research is to develop a video compression framework for HAS deployments, as shown in Figure 1. The input parameters from the streaming service provider are the target encoding speed, maximum quality, target *Just Noticeable Difference* (JND) in quality perception, and other a priori information like target bitrates and encoders/codecs used. According to

[1]https://www.ericsson.com/assets/local/reports-papers/mobility-report/documents/2020/november-2020-ericsson-mobility-report.pdf, last access: May 10, 2022.

[2]https://bitmovin.com/compression-standards-vvc-2020/, last access: May 10, 2022.
[3]https://bitmovin.com/multi-codec-world-2020/, last access: May 10, 2022.

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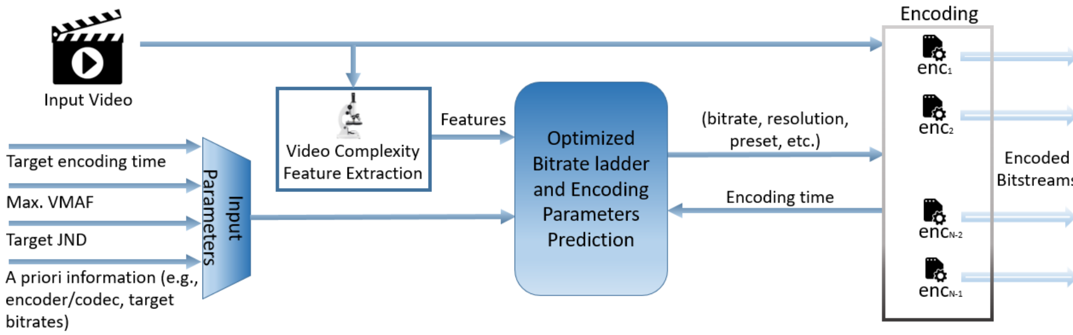

Figure 1: The ideal video compression system for HAS envisioned in this doctoral study.

these inputs and the video, optimized bitrate-ladder and encoding parameters are predicted for fast and compression-efficient streaming. It proposes novel video coding enhancement schemes using cutting-edge algorithms. The problem of increasing the computational complexity of encoding multiple versions of the same content with numerous video codecs by maintaining similar compression efficiency is explored. Content-adaptive encoding optimization algorithms are proposed for *Video on Demand* (VoD) and live streaming applications.

Paper Organization: The current state-of-the-art in this field is reviewed in Section 2. Section 3 and Section 4 discuss the research questions and the proposed methodology. The publications are listed in Section 5. Section 6 and Section 7 describe the reproducibility of the research and its future directions, respectively. Finally, Section 8 concludes the paper with a summary of the presented research.

2 RELATED WORKS

Numerous algorithms are proposed for fast multi-rate encoding ranging from limiting CU depth search levels [2, 30, 31] to reusing additional available information to help with other encoding decisions [29, 38]. Fast multi-rate methods include multi-encoding and multi-resolution encoding optimizations [9, 15] to each video at various bitrates and spatial resolution representations. Reznik *et al.* [28] addressed the problem of designing encoding profiles for AVC and HEVC codecs such that the overall quality delivered by such a system is optimal. x265 encoder[4] has integrated a few analysis reuse strategies using x264 AVC encoder[5] analysis metadata to accelerate the encoding process.

There are approaches proposed in the literature for shot detection, content-adaptive block partitioning prediction [39], adaptive quantization parameter prediction, and much more in the domain of content-adaptive encoding[6]. Ramachandran *et al.* [27] and Shoham *et al.* [32] proposed content-adaptive controls for video encoding for live encoding applications. According to the Bitmovin Video Developer Report 2021[7], *live streaming at scale* has the highest scope for innovation in video streaming services. Though per-title encoding schemes [1, 7] improve the quality of video delivery, *convex-hull* computation is expensive, making it suitable for only VoD streaming applications. Some schemes pre-analyze the video contents to avoid brute force encoding of all bitrate-resolution pairs[8]. Katsenou *et al.* [12] introduced a content-gnostic method that employs machine learning to find the bitrate range for each resolution that outperforms other resolutions. Bhat *et al.* [4, 5] proposed a Random Forest (RF) classifier to determine which encoding resolution is the best suited over various quality ranges and to study machine learning-based adaptive resolution prediction. However, these approaches yield *latency* much higher than the accepted latency in live streaming. Furthermore, Amirpour *et al.* [1] demonstrated that framerate should be considered during convex-hull computation of *High Framerate* (HFR) videos.

3 RESEARCH QUESTIONS

This section introduces the four research questions being investigated.

(1) **How to provide fast and compression-efficient multi-bitrate and multi-resolution representations in HAS?**
As the demand for higher resolution, framerate, and bitrate content rises, more video codecs are also introduced to deliver high-quality content. It means that the number of representations needed for HAS is increasing. There are various limitations to the multiple attempts in the literature which provide efficient multi-bitrate and multi-resolution encoding schemes. The overall encoding time is bound by the encoding time of the highest bitrate representation of the highest resolution in a few schemes [2, 30, 31]. In contrast, in some cases, the ratio of compression efficiency to the encoding time reduction is very high [9, 15]. Multi-encoding algorithms are crucial to reducing the encoding time while maintaining the compression efficiency similar to the standalone encodings.

(2) **How to provide fast and compression-efficient multi-codec representations for HAS?**
HAS serves multiple types of devices- a subset of gadgets can only decode the previous generation codecs (*e.g.*, AVC),

[4]https://www.videolan.org/developers/x265.html, last access: May 10, 2022.
[5]https://www.videolan.org/developers/x264.html, last access: May 10, 2022.
[6]https://www.ittiam.com/content-adaptive-encoding-key-decisions-effective-solution/, last access: May 10, 2022.
[7]https://go.bitmovin.com/video-developer-report, last access: May 10, 2022.
[8]https://bitmovin.com/whitepapers/Bitmovin-Per-Title.pdf, last access: May 10, 2022.

another subset of devices can only decode the current generation codec (*e.g.*, HEVC), and where the third sub-set of devices can decode both codecs and can also seamlessly switch between them. This means representations of both codecs should be stored to address multiple clients. The goal here is to reduce the increased computational complexity of encoding representations of multiple codecs without compromising the overall quality of such a system. In the future, the attention shifts to accelerating the next generation codec (*e.g.*, VVC) using HEVC encoder analysis information.

(3) **How to improve the speed and compression performance of encoder using content-adaptive algorithms?** The quest for achieving a perfect trade-off between perceptual quality and compression efficiency inspires us to find the most effective way for optimal bit allocation for a video, for which Content Adaptive Encoding (CAE) solutions are a good choice. By allocating only the required bits for a given video, CAE can drive significant bitrate savings based on complexity. Another approach is to improve the QoE by spending the same bits. It is targeted to *derive the video's content-adaptive spatial and temporal features*, which can be later used to influence encoder decisions like slice-type, quantization parameter, block partitioning, and much more.

(4) **How to improve the speed and compression efficiency of per-title encoding for live-streaming applications?** For live HAS applications, the raw video is encoded at multiple bitrates, resolutions, codecs, etc., though we are constrained in terms of encoding time. The goal is to decrease the time to compute the convex-hull for each title by analyzing the video using certain features [7]. Typically, the encoders have presets with conservative settings biased toward the compression efficiency [27]. It is targeted to research *dynamically configuring the encoder parameters on the fly* to sustain a target encoding speed according to the content for efficient live streaming.

4 RESEARCH METHODOLOGY

In this research, an Iterative and Incremental Development (IID) approach [14] is used to *(i)* design, *(ii)* develop, and *(iii)* evaluate proposed solutions. This approach helps to learn during the development of the earlier parts or versions of the solution and apply modifications to the next steps if needed [8]. An experimental approach where the proposed tools and methods are evaluated and validated using controlled experiments through objective or subjective evaluations is used in this study. Published papers listed in Section 5 are a few examples of this approach. With empirical research methods, hypotheses are formed based on the research questions from Section 3. These hypotheses will be quantitatively, rigorously analyzed, and evaluated according to established research methods. Furthermore, the outcomes and results of this thesis shall be reported by presenting quantitative research results.

5 PUBLICATIONS

Table 1 provides a list of papers where the first author is the author of this paper and are designed to investigate further the research questions stated in Section 3.

In this doctoral research, a DCT-based energy function is introduced to determine the block-wise texture of each frame [10, 13]. The texture is averaged to determine the *spatial energy* feature denoted as E. Furthermore, the block-wise sum of absolute difference (*SAD*) of the texture energy of each frame compared to its previous frame is computed to obtain the *temporal energy* (h). These features can be an ideal replacement for the state-of-the-art SI and TI [11] features and are used in the video complexity analysis step (*cf.* Figure 1) to infer encoding parameters. The gradient of h feature is used to segment video into multiple shots for encoding in *Video on Demand* (VoD) *HTTP Adaptive Streaming* (HAS) applications [18]. The proposed shot detection algorithm has a recall rate of 25% and an F-measure of 20% greater than the default shot detection algorithm implemented in the x265 encoder. Furthermore, an Intra CU depth Prediction (`INCEPT`) algorithm is proposed, which limits *Rate-Distortion Optimization* (RDO) for each CTU in HEVC by utilizing the spatial correlation with the neighboring CTUs, which is computed using the E feature [24]. `INCEPT` achieves an average 23.34% reduction in encoding time while incurring only a 1.67% increase in bitrate than the original coding in the x265 encoder.

To address the research question 4, an online bitrate ladder construction scheme based on dynamic resolution prediction is proposed for live video streaming applications [21]. In this scheme, each target bitrate's optimized resolution is determined from any pre-defined set of resolutions using each video segment's E and h features. A *perceptually-aware* per-title encoding (`PPTE`) scheme for video streaming applications is introduced where optimized bitrate-resolution pairs are predicted online based on JND in quality perception to avoid adding perceptually similar representations in the bitrate ladder [22]. On average, `PPTE` yields bitrate savings of 16.47% and 27.02% to maintain the same PSNR and VMAF, respectively, compared to the reference *HTTP Live Streaming* (HLS) bitrate ladder without any noticeable additional latency in streaming accompanied by a 30.69% cumulative decrease in storage space for various representations.

Other than predicting resolution and bitrate for encoding, a *co*ntent-aware frame *d*ropping *a*lgorithm (`CODA`) to drop frames uniformly in every video (segment) according to the target bitrate and E and h features is proposed [19]. The *optimized framerate* for every target bitrate is determined dynamically, yielding the highest compression efficiency. On average, `CODA` reduces the overall *Ultra High Definition* (UHD) HFR encoding time using x265 by 21.82%, with bitrate savings of 15.87% and 18.20% to maintain the same PSNR and VMAF scores, respectively, compared to the original framerate encoding. Furthermore, a fast and efficient per-title encoding scheme, `Live-PSTR` is proposed tailor-made for live UHD HFR streaming [17]. It includes a pre-processing step in which E and h features are used to determine the complexity of each video segment, based on which the optimized encoding resolution and framerate for streaming at every target bitrate are determined. An optimized constant rate factor (CRF) prediction scheme is proposed, where E and h features of every video segment are extracted to predict each target bitrate's optimal CRF for the constrained variable bitrate (cVBR) encoding [20].

In [23], various multi-encoding schemes (*i.e.*, multi-rate and multi-resolution) are investigated, and multi-encoding schemes are proposed for large-scale HTTP Adaptive Streaming deployments.

Table 1: List of Related Publications

Row	Title	Venue	Rank[1]	Status	Ref.
1	Efficient Multi-Encoding Algorithms for HTTP Adaptive Bitrate Streaming	Picture Coding Symposium (PCS) 2021	B1	Published	[23]
2	Efficient Content-Adaptive Feature-based Shot Detection for HTTP Adaptive Streaming	International Conference on Image Processing (ICIP) 2021	A1	Published	[18]
3	INCEPT: Intra CU depth Prediction for HEVC	International Workshop on Multimedia Signal Processing (MMSP) 2021	B2	Published	[24]
4	OPTE: Online Per-title Encoding	International Conference on Acoustics, Speech, and Signal Processing (ICASSP) 2022	A1	Published	[21]
5	CODA: Content-Adaptive Frame dropping Algorithm	Data Compression Conference (DCC) 2022	A2	Published	[19]
6	Live-PSTR: Live Per-title Encoding for Ultra HD Adaptive Streaming	NAB Broadcast Engineering and Information Technology (BEIT) Conference 2022	-	Accepted	[17]
7	Perceptually-aware Per-title Encoding for Adaptive Video Streaming	International Conference on Multimedia & Expo (ICME) 2022	A1	Accepted	[22]
8	OPSE: Online Per-Scene Encoding for Adaptive HTTP Live Streaming	International Conference on Multimedia & Expo Workshop (ICMEW) 2022	-	Accepted	[16]
9	VCA: Video Complexity Analyzer	Multimedia Systems Conference (MMSys) 2022	-	Published	[25]
10	ETPS: Efficient Two-Pass encoding Scheme for Live Adaptive Streaming	ICIP 2022	A1	Accepted	[20]

[1] http://www.conferenceranks.com/, accessed May 10, 2022.

The proposed multi-encoding scheme optimized for the highest compression efficiency reduces the overall x265 HEVC encoding time by 39%, with a 1.5% bitrate increase compared to standalone encodings. Its optimized version for the highest time savings reduces the overall encoding time by 50%, with a 2.6% bitrate increase compared to standalone encodings.

6 REPRODUCIBILITY

To ensure that the research outcomes of the doctoral study are beneficial to the video streaming community across the globe, VCA Video Complexity Analyzer open-source project[9] [25] is launched, which is a practical implementation of the algorithms/ schemes proposed in this doctoral research. For example, the proposed shot-detection algorithm [18] is implemented in VCA as an application of the complexity analysis. Dynamic resolution prediction for a given set of target bitrates [21] is also implemented as another application inside VCA. The software also supports multi-threading and x86 Single Instruction Multiple Data (SIMD) accelerations [35]. The architecture of content-adaptive encoding using VCA is shown in Figure 2. Furthermore, the proposed multi-encoding schemes [23] are implemented in the x265 HEVC encoder and hosted in GitHub[10].

7 FUTURE DIRECTIONS

In this doctoral study, multi-encoding schemes were analyzed only in serial encoding perspective [23]. In the future, novel schemes shall be designed for parallel encoding environments. Furthermore, the research question 2, *i.e.*, efficient multi-codec encoding, shall be investigated. Similar to the resolution, bitrate, quality, and framerate prediction using the proposed spatio-temporal features, optimized encoding preset, and optimized encoding hardware configuration prediction shall be investigated to achieve *zero-latency* encoding for adaptive live streaming applications.

[9] https://github.com/cd-athena/VCA, last access: May 10, 2022
[10] https://github.com/cd-athena/x265_multiencoding, last access: May 10, 2022

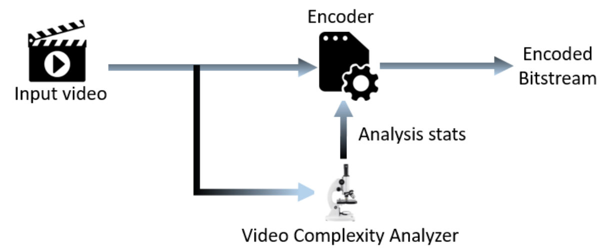

Figure 2: VCA in content-adaptive encoding systems.

8 SUMMARY

This paper presents research questions tailor-made toward an efficient video coding system for HAS. The related works are briefly reviewed, and the methodology used in this research is discussed. The publications, ongoing works, and future work related to doctoral research have been presented. Finally, the measures taken to ensure the reproducibility of the work are discussed.

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REFERENCES

[1] Hadi Amirpour, Christian Timmerer, and Mohammad Ghanbari. 2021. PSTR: Per-Title Encoding Using Spatio-Temporal Resolutions. In *2021 IEEE International Conference on Multimedia and Expo (ICME)*. 1–6. https://doi.org/10.1109/ICME51207.2021.9428247

[2] Hadi Amirpour, Ekrem Çetinkaya, Christian Timmerer, and Mohammad Ghanbari. 2020. Fast Multi-rate Encoding for Adaptive HTTP Streaming. In *2020 Data Compression Conference (DCC)*. 358–358.

[3] Abdelhak Bentaleb, Bayan Taani, Ali C. Begen, Christian Timmerer, and Roger Zimmermann. 2019. A Survey on Bitrate Adaptation Schemes for Streaming Media Over HTTP. *IEEE Communications Surveys Tutorials* 21, 1 (2019), 562–585. https://doi.org/10.1109/COMST.2018.2862938

[4] Madhukar Bhat, Jean-Marc Thiesse, and Patrick Le Callet. 2020. A Case Study of Machine Learning Classifiers for Real-Time Adaptive Resolution Prediction in Video Coding. In *2020 IEEE International Conference on Multimedia and Expo (ICME)*. 1–6. https://doi.org/10.1109/ICME46284.2020.9102934

[5] Madhukar Bhat, Jean-Marc Thiesse, and Patrick Le Callet. 2021. Combining Video Quality Metrics To Select Perceptually Accurate Resolution In A Wide Quality Range: A Case Study. In *2021 IEEE International Conference on Image Processing (ICIP)*. 2164–2168. https://doi.org/10.1109/ICIP42928.2021.9506310

[6] B. Bross, Jianle Chen, Shan Liu, and Ye-Kui Wang. 2020. JVET-S2001 Versatile Video Coding (Draft 10). *Joint Video Exploration Team (JVET) of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29/WG* 11 (2020).

[7] Jan De Cock, Zhi Li, Megha Manohara, and Anne Aaron. 2016. Complexity-based consistent-quality encoding in the cloud. In *2016 IEEE International Conference on Image Processing (ICIP)*. https://doi.org/10.1109/ICIP.2016.7532605

[8] Peter J. Denning, Douglas E Comer, David Gries, Michael C. Mulder, Allen Tucker, A. Joe Turner, and Paul R Young. 1989. Computing as a discipline. *Computer* 22, 2 (1989), 63–70.

[9] Kalyan Goswami, Bhavna Hariharan, Pradeep Ramachandran, Alex Giladi, Dan Grois, Kavitha Sampath, Aruna Matheswaran, Ashok Kumar Mishra, and Kevin Pikus. 2018. Adaptive Multi-Resolution Encoding for ABR Streaming. In *2018 25th IEEE International Conference on Image Processing (ICIP)*. 1008–1012. https://doi.org/10.1109/ICIP.2018.8451485

[10] N B Harikrishnan, Vignesh V Menon, Manoj S Nair, and Gayathri Narayanan. 2017. Comparative evaluation of image compression techniques. In *2017 International Conference on Algorithms, Methodology, Models and Applications in Emerging Technologies (ICAMMAET)*. 1–4. https://doi.org/10.1109/ICAMMAET.2017.8186637

[11] ITU-T. 2021. P.910 : Subjective video quality assessment methods for multimedia applications. https://www.itu.int/rec/T-REC-P.910-202111-I/en

[12] Angeliki V. Katsenou, Joel Sole, and David R. Bull. 2019. Content-gnostic Bitrate Ladder Prediction for Adaptive Video Streaming. In *2019 Picture Coding Symposium (PCS)*. https://doi.org/10.1109/PCS48520.2019.8954529

[13] Michael King, Zinovi Tauber, and Ze-Nian Li. 2007. A New Energy Function for Segmentation and Compression. In *2007 IEEE International Conference on Multimedia and Expo*. 1647–1650. https://doi.org/10.1109/ICME.2007.4284983

[14] Craig Larman and Victor R Basili. 2003. Iterative and incremental developments. a brief history. *Computer* 36, 6 (2003), 47–56.

[15] Aruna Mathesawaran, Praveen Kumar Karadugattu, Pradeep Ramachandran, Alex Giladi, Dan Grois, Pooja Venkatesan, and Alex Balk. 2020. Open source framework for reduced-complexity multi-rate HEVC encoding. In *Applications of Digital Image Processing XLIII*, Andrew G. Tescher and Touradj Ebrahimi (Eds.), Vol. 11510. International Society for Optics and Photonics, SPIE, 461 – 471. https://doi.org/10.1117/12.2567877

[16] Vignesh V Menon, Hadi Amirpour, Christian Feldmann, Mohammad Ghanbari, and Christian Timmerer. 2022. OPSE: Online Per-Scene Encoding for Adaptive HTTP Live Streaming. In *2022 IEEE International Conference on Multimedia and Expo Workshop (ICMEW)* (Taiwan) *(ICMEW '22)*.

[17] Vignesh V Menon, Hadi Amirpour, Christian Feldmann, Adithyan Ilangovan, Martin Smole, Mohammad Ghanbari, and Christian Timmerer. 2022. Live-PSTR: Live Per-title Encoding for Ultra HD Adaptive Streaming. In *Proceedings of the NAB Broadcast Engineering and Information Technology (BEIT) Conference* (Las Vegas, US) *(BEIT '22)*.

[18] Vignesh V Menon, Hadi Amirpour, Mohammad Ghanbari, and Christian Timmerer. 2021. Efficient Content-Adaptive Feature-Based Shot Detection for HTTP Adaptive Streaming. In *2021 IEEE International Conference on Image Processing (ICIP)*. 2174–2178. https://doi.org/10.1109/ICIP42928.2021.9506092

[19] Vignesh V Menon, Hadi Amirpour, Mohammad Ghanbari, and Christian Timmerer. 2022. CODA: Content-aware Frame Dropping Algorithm for High Framerate Video Streaming. In *2022 Data Compression Conference (DCC)*. 475–475. https://doi.org/10.1109/DCC52660.2022.00086

[20] Vignesh V Menon, Hadi Amirpour, Mohammad Ghanbari, and Christian Timmerer. 2022. ETPS: Efficient Two-pass Encoding Scheme for Adaptive Live Streaming. In *2022 IEEE International Conference on Image Processing (ICIP)*.

[21] Vignesh V Menon, Hadi Amirpour, Mohammad Ghanbari, and Christian Timmerer. 2022. OPTE: Online Per-Title Encoding for Live Video Streaming. In *ICASSP 2022 - 2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. 1865–1869. https://doi.org/10.1109/ICASSP43922.2022.9746745

[22] Vignesh V Menon, Hadi Amirpour, Mohammad Ghanbari, and Christian Timmerer. 2022. Perceptually-aware Per-title Encoding for Adaptive Video Streaming. In *2022 IEEE International Conference on Multimedia and Expo (ICME)* (Taiwan) *(ICME '22)*.

[23] Vignesh V Menon, Hadi Amirpour, Christian Timmerer, and Mohammad Ghanbari. 2021. Efficient Multi-Encoding Algorithms for HTTP Adaptive Bitrate Streaming. (2021), 1–5. https://doi.org/10.1109/PCS50896.2021.9477499

[24] Vignesh V Menon, Hadi Amirpour, Christian Timmerer, and Mohammad Ghanbari. 2021. INCEPT: Intra CU Depth Prediction for HEVC. In *2021 IEEE 23rd International Workshop on Multimedia Signal Processing (MMSP)*. 1–6. https://doi.org/10.1109/MMSP53017.2021.9733517

[25] Vignesh V Menon, Christian Feldmann, Hadi Amirpour, Mohammad Ghanbari, and Christian Timmerer. 2022. VCA: Video Complexity Analyzer. In *13th ACM Multimedia Systems Conference (MMSys '22) (MMSys '22)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3524273.3532896

[26] J. Ohm, Gary J Sullivan, Heiko Schwarz, Thiow Keng Tan, and Thomas Wiegand. 2012. Comparison of the coding efficiency of video coding standards—including high efficiency video coding (HEVC). *IEEE Transactions on circuits and systems for video technology* 22, 12 (2012), 1669–1684.

[27] Pradeep Ramachandran, Shushuang Yang, Praveen Tiwari, and Gopi Akisetty. 2020. Content adaptive live encoding with open source codecs. 345–348. https://doi.org/10.1145/3339825.3393580

[28] Yury Reznik, Xiangbo Li, Karl O. Lillevold, Abhijith Jagannath, and Justin Greer. 2019. Optimal Multi-Codec Adaptive Bitrate Streaming. In *2019 IEEE International Conference on Multimedia Expo Workshops (ICMEW)*. 348–353. https://doi.org/10.1109/ICMEW.2019.00066

[29] Damien Schroeder, Adithyan Ilangovan, Martin Reisslein, and Eckehard Steinbach. 2018. Efficient Multi-Rate Video Encoding for HEVC-Based Adaptive HTTP Streaming. *IEEE Transactions on Circuits and Systems for Video Technology* 28, 1 (Jan 2018), 143–157. https://doi.org/10.1109/TCSVT.2016.2599028

[30] Damien Schroeder, Adithyan Ilangovan, and Eckehard Steinbach. 2015. Multi-rate encoding for HEVC-based adaptive HTTP streaming with multiple resolutions. In *2015 IEEE 17th International Workshop on Multimedia Signal Processing (MMSP)*. 1–6. https://doi.org/10.1109/MMSP.2015.7340822

[31] Damien Schroeder, Patrick Rehm, and Eckehard Steinbach. 2015. Block structure reuse for multi-rate high efficiency video coding. In *2015 IEEE International Conference on Image Processing (ICIP)*. 3972–3976.

[32] Tamar Shoham, Dror Gill, Sharon Carmel, Nikolay Terterov, and Pavel Tiktov. 2019. Content-adaptive frame level rate control for video encoding using a perceptual video quality measure. In *Applications of Digital Image Processing XLII*, Vol. 11137. SPIE, 164 – 177.

[33] Thomas Stockhammer. 2011. Dynamic Adaptive Streaming over HTTP – Standards and Design Principles. In *ACM Conference on Multimedia Systems*. 133–144.

[34] Gary J. Sullivan, Jens-Rainer Ohm, Woo-Jin Han, and Thomas Wiegand. 2012. Overview of the high efficiency video coding (HEVC) standard. *IEEE Transactions on circuits and systems for video technology* 22, 12 (2012), 1649–1668.

[35] Praveen Kumar Tiwari, Vignesh V Menon, Jayashri Murugan, Jayashree Chandrasekaran, Gopi Satykrishna Akisetty, Pradeep Ramachandran, Sravanthi Kota Venkata, Christopher A Bird, and Kevin Cone. 2018. Accelerating x265 with Intel® Advanced Vector Extensions 512. *White Paper on the Intel Developers Page* (2018). https://www.intel.com/content/dam/develop/external/us/en/documents/mcw-intel-x265-avx512.pdf

[36] Thomas Wiegand, Gary J. Sullivan, Gisle Bjøntegaard, and Ajay Luthra. 2003. Overview of the H.264/AVC video coding standard. *IEEE Transactions on Circuits and Systems for Video Technology* 13, 7 (2003), 560–576. https://doi.org/10.1109/TCSVT.2003.815165

[37] Anatoliy Zabrovskiy, Christian Feldmann, and Christian Timmerer. 2018. Multi-Codec DASH Dataset. In *Proceedings of the 9th ACM Multimedia Systems Conference* (Amsterdam, Netherlands) *(MMSys '18)*. Association for Computing Machinery, New York, NY, USA, 438–443. https://doi.org/10.1145/3204949.3208140

[38] André Zaccarin and Boon-Lock Yeo. 2002. Multi-rate encoding of a video sequence in the DCT domain. In *2002 IEEE International Symposium on Circuits and Systems. Proceedings (Cat. No.02CH37353)*, Vol. 2. II–II.

[39] Y. Zhang, Na Li, Sam Kwong, Gangyi Jiang, and Huanqiang Zeng. 2019. Statistical Early Termination and Early Skip Models for Fast Mode Decision in HEVC INTRA Coding. *ACM Trans. Multimedia Comput. Commun. Appl.* 15, 3, Article 70 (7 2019), 23 pages. https://doi.org/10.1145/3321510