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Comparing V-Nova LCEVC SDK with Practical Open-Source Video Codecs

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Abstract—
This paper presents a comparative evaluation of the V-Nova LCEVC SDK against several practical open-source video encoders, namely SVT-AV1, XEVE, VVenC, x265, and x264. We analyze the trade-offs between the compression efficiency and encoder/decoder runtime of these encoders for high-resolution (UHD and HD) 10-bit consumer applications under a random access configuration. Rate–distortion behavior is assessed using Video Multimethod Assessment Fusion (VMAF, and VMAF-NEG) and Peak Signal-to-Noise Ratio (PSNR), while computational cost is measured through the encoder/decoder runtime. We also analyze the impact of LCEVC's enhancement layer in terms of both bitrate increase and rate–distortion improvement. The results show that V-Nova LCEVC SDK delivers notable reductions in encoding time with respect to its base codecs, highlighting its suitability as a low-complexity enhancement layer. By comparison, VVenC exhibits a strong compression performance at the expense of high complexity, XEVE also displays considerable encoding times, and SVT-AV1 offers a more balanced compromise between efficiency and computational requirements.

■ **INTRODUCTION** Across today's consumer electronics ecosystem, video compression plays a central role in enabling modern multimedia experiences on a wide range of devices and services, including smart TVs, smartphones, tablets, gaming consoles, and virtual and augmented reality (VR/AR) platforms. Consumer-facing applications such as over-the-top (OTT) video streaming, cloud gaming, social media video sharing, and real-time video communication impose strict constraints not only on compression efficiency, but also on encoding and decoding complexity, latency, and energy consumption. In this context, practical encoder

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implementations are the ones effectively deployed in consumer products and services rather than reference software. Decisions made by content providers and device manufacturers often involve trade-offs between compression efficiency, computational cost, real-time capability, and backward compatibility with legacy devices. Consequently, evaluating the performance of practical video codecs under realistic configurations is essential to understand their suitability for consumer electronics applications.

In recent decades, various image and video coding techniques have been explored, and some of them have been included in the video coding standards issued by the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC), the Motion Pictures Expert Group (MPEG) and the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) Video Coding Experts Group (VCEG).

VCEG developed the recommendations H.261 in 1988, and H.263 in 1996. MPEG developed MPEG-1 in 1993, MPEG-4 in 1999, Essential Video Coding (EVC) in 2020, and Low Complexity Enhancement Video Coding (LCEVC) in 2021. Through the establishment of joint teams, including experts from both MPEG and VCEG, the two organizations also developed joint specifications, such as MPEG-2 in 1996, H.264/Advanced Video Coding (AVC) in 2003, H.265/High-Efficiency Video Coding (HEVC) in 2013, and H.266/Versatile Video Coding (VVC) in 2020. This landscape is completed by the Alliance for Open Media (AOM), which introduced the first version of AV1 (AOMedia Video 1) in 2018. The development of the AV1 video coding specification considered not only technical aspects but also patent-related concerns throughout the process.

Of all these standards, LCEVC deserves special mention because it is not designed to be an alternative to other existing and emerging video coding standards, but rather a standalone toolset for the enhancement of any other existing (and future) video codec. LCEVC has recently gained the attention of the industrial and scientific communities due to its characteristic of providing a low-complexity enhancement layer compatible with existing standards.

Given the rapid evolution of video compression standards, it is essential to conduct comparative studies that highlight the advantages and trade-offs of existing codecs. Single-layer standards and formats, such as AVC, HEVC, AV1, EVC, and VVC represent a progression in compression efficiency, with each new generation achieving higher levels of data reduction while simultaneously increasing computational complexity. By contrast, LCEVC follows a different approach by using a multi-layer structure, potentially offering a better balance between compression efficiency, computational requirements, and visual quality. A detailed analysis comparing these technologies is necessary to provide a clear understanding of their relative strengths and weaknesses, guiding researchers, industry professionals, and content providers in selecting the most suitable codec for their specific applications.

Traditionally, together with each of the video coding standards, a reference encoder implementation has also been developed to evaluate the performance of the coding tools included in them. Such reference encoders are used during the video standardization process for research purposes and as a reference for implementers. Generally, these encoders are the first software implementation for a standard and are not used for production. Afterwards, optimized encoders developed by the open-source community or commercial entities are released. These practical implementations are deployed by companies for their encoding needs and are subject to stricter speed and resource constraints. Therefore, the performance of reference and practical encoders might be substantially different. The former have been widely studied in the literature, but the latter have not.

To support informed decision-making, the main contribution of this paper is a comparative performance evaluation of the V-Nova LCEVC SDK against several recent and practical open-source video encoders, namely: SVT-AV1 (AV1), XEVE (EVC), VVenC (VVC), x265 (HEVC), and x264 (AVC). By systematically analyzing the trade-offs between compression efficiency and encoding/decoding runtime under conditions representative of real-world consumer video delivery, namely 10-bit Ultra-High-Definition (UHD) and High-Definition (HD) applications using random-access configuration, our study offers valuable insights for consumer-oriented streaming services, content distributors, and system integrators who must choose the most suitable encoder for their specific technical and economic constraints. This comprehensive approach differs from prior studies of the state of the art, which usually focus on a limited subset of video encoders or overlook practical constraints relevant to consumer-grade hardware and services.

The remainder of this paper is organized as follows. The next section provides information on the video codecs used and the standards or video coding specifications they comply with, followed by a review of related work. We then describe the test conditions, configurations, and the metrics employed, as well as the evaluation methodology. Subsequently, the results are presented, and we then conclude the paper with a discussion of future work.

STANDARDS OVERVIEW

This section presents a brief overview of the standards followed by the encoder implementations analyzed in this study. We outline their main characteristics, fundamental principles, and common applications, providing a foundation for the subsequent analysis and evaluation.

AVC

AVC [1] is one of the most widely used video compression standards, and was designed to deliver high-quality video at lower bit rates. Developed jointly by the ITU-T VCEG and the ISO/IEC MPEG, it was standardized in 2003 and has since become the dominant format for digital video applications. AVC achieves greater compression efficiency than its predecessors through the use of more advanced techniques such as inter-frame and intra-frame prediction, motion compensation, variable block-size encoding, and sophisticated entropy coding methods such as Context-Adaptive Binary Arithmetic Coding (CABAC) and Context-Adaptive Variable-Length Coding (CAVLC). These optimizations enable a significant reduction in bit rate without a noticeable loss of quality, making it ideal for bandwidth-constrained environments. As a result, AVC is nowadays widely adopted in video streaming services, video conferencing, Blu-ray discs, digital television broadcasting, and surveillance systems, among many other applications.

One of the most popular software implementations for AVC is x264 [2], an open-source codec known for its high efficiency and flexibility. The x264 encoder provides excellent compression performance, allowing users to achieve high video quality while maintaining low file sizes. It supports a wide range of encoding settings, including multi-pass encoding, adaptive quantization, and various preset configurations to balance speed and quality.

HEVC

HEVC [3], also known as H.265, is the successor to H.264/AVC and was developed by the Joint Collaborative Team on Video Coding (JCT-VC), a partnership between the ITU-T VCEG and the ISO/IEC MPEG. Officially standardized in 2013, HEVC was designed to provide significantly improved compression efficiency, achieving up to a 50% bit rate reduction for the same visual quality compared with AVC. This is particularly beneficial for high-resolution content, including 4K and 8K video, as well as video streaming over bandwidth-constrained networks. HEVC introduces several key advancements, such as a more flexible block structure with Coding Tree Units (CTUs), improved motion compensation and prediction techniques, and more efficient entropy coding using CABAC. These enhancements enable better video quality at lower bit rates, leading to HEVC being widely used in applications such as streaming services, Ultra HD Blu-ray, and video conferencing.

One of the most popular open-source implementations *for* HEVC is x265 [4], which is widely used for video encoding due to its high efficiency and extensive feature set. x265 is designed to optimize compression while maintaining high video quality, offering a range of encoding presets and tunable parameters to balance speed and efficiency. It supports advanced encoding techniques such as adaptive quantization, rate-distortion (R-D) optimization, and multi-pass encoding to achieve optimal results.

VVC

VVC, also known as H.266, is the latest international video coding standard, finalized in July 2020 by the Joint Video Experts Team (JVET) [5]. VVC was developed to provide substantial improvements in compression efficiency, achieving around a 50% bit rate reduction compared with its predecessor, HEVC, while maintaining the same visual quality. This enhanced efficiency makes VVC particularly well-suited for high-resolution content, such as 4K, 8K, high dynamic range (HDR), 360° video, and immersive media applications. Key advancements in VVC include a more flexible block partitioning scheme, improved motion prediction techniques, adaptive loop filtering, and support for more efficient entropy coding. These improvements enable VVC to deliver a higher video quality at lower bit rates, making it an ideal choice for modern streaming services, broadcasting, and emerging video applications.

One of the most optimized open-source implementations for VVC is VVenC, which was developed by Fraunhofer HHI [6], [7]. VVenC is designed to provide

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a highly efficient and practical encoder implementation. It offers multiple encoding presets that allow users to balance encoding speed and compression efficiency.

EVC

EVC is a video compression standard developed as part of MPEG-5 to provide an efficient and licensing-friendly alternative to existing codecs [8]. Finalized in 2020, EVC aims to balance high compression efficiency with clear and transparent licensing terms. It defines two distinct profiles: the Baseline profile, which includes only royalty-free coding tools, ensuring broad accessibility and adoption, and the Main profile, which enhances compression performance by incorporating additional proprietary technologies. This dual-profile approach allows users to choose between a completely royalty-free solution or a more efficient codec with additional features that may require licensing. EVC is designed to support a range of applications, including video streaming, broadcasting, and real-time communications, while maintaining competitive compression efficiency compared with previous standards such as AVC and HEVC.

A key open-source implementation for EVC is XEVE, which serves as the reference encoder for the standard. XEVE is optimized for efficiency and flexibility, allowing users to experiment with both the Baseline and Main profiles. The software provides configurable encoding options to balance compression performance and computational complexity. It is available on GitHub [9] for both academic and commercial use, making it a valuable tool for research and industry adoption. With its focus on accessibility and performance, XEVE plays a crucial role in demonstrating the capabilities of EVC and facilitating its deployment in real-world applications.

LCEVC

LCEVC is a video compression standard developed by MPEG and finalized in 2021 [10]. Unlike traditional standards, LCEVC is not a standalone video compression scheme, but rather an enhancement layer that works on top of a base layer encoded using a different standard such as AVC, HEVC, EVC, or VVC. By adding one or two enhancement layers, LCEVC refines the quality of a base layer encoded at a lower resolution. Some of the techniques used by LCEVC include adaptive upsampling (which can incorporate sharpening filters), lightweight residual coding, and post-processing capabilities such as dithering, which can provide a significant boost in perceived quality, although objective metrics typically report worse quality results. This multi-layer approach, combined with simple techniques, allows LCEVC to enhance subjective video quality without significantly increasing encoding or decoding complexity, making it well-suited for applications such as live streaming, broadcasting, and cloud gaming. Its design facilitates compatibility with existing hardware and software, reducing the need for costly infrastructure upgrades.

V-Nova is the main driving force behind LCEVC and has developed one of its most optimized codecs [11]. For this study, V-Nova provided an LCEVC-enhanced version of AVC and HEVC known as V-Nova LCEVC SDK. Although support for other codecs, including VVC and EVC, it is already available but was not provided for this evaluation. V-Nova's implementation integrates LCEVC as an enhancement layer for multiple encoders, leveraging its unique ability to improve the coding efficiency of the base codec at full resolution while minimizing encoding complexity. This flexibility makes LCEVC an attractive solution for content delivery networks, video streaming platforms, and real-time applications where computational efficiency is critical.

AV1

In addition to video encoding standards, other video coding specifications have been developed that offer notable bit rate savings and hold significant relevance. One such example is AV1, an open video coding specification specifically designed for internet-based video transmission. Developed as the successor to VP9, AV1 was created by the Alliance for Open Media, a consortium established in 2015. Officially released in March 2018, its goal was to unify the technologies and expertise of its members to deliver a high-efficiency video format optimized for web and browser-based applications [12]. The AV1 video coding specification is already supported by many web platforms, including Android, Chrome, Microsoft Edge, and Firefox, and it has been widely adopted by major consumer streaming platforms such as YouTube, Netflix and Vimeo.

One of the most optimized open-source implementations for AV1 is SVT-AV1 [13], which is designed to yield excellent quality-speed-latency tradeoffs on CPU platforms for a wide range of video coding applications. The SVT-AV1 encoder is based on the SVT (Scalable Video Technology) architecture, which supports multi-dimensional parallelism, multi-pass partitioning decision-making, multi-stage/multi-class mode decision-making, and multi-level spatio-temporal prediction and residual coding algorithms.

Table 1 summarizes the encoding goals and typical use cases of the evaluated codecs, highlighting their intended applications and deployment scenarios across different video delivery contexts.

RELATED WORK

Recent evaluations of practical video encoders have highlighted key trade-offs among various standards. Valiandi et al. [14] compare six video codecs compliant with VVC, AV1, EVC, HEVC, and VP9, using datasets that comprise multiple resolutions. Their findings indicate that VVC provides substantial bit rate savings, outperforming AV1 by an average of 38.5% in the Bjøntegaard Delta rate (BD-rate) on high-resolution content. AV1 and VVC both surpass HEVC, with VVC showing gains that reach up to 47% in higher resolution formats. In their comparative assessment, the authors utilize the slowest possible encoding preset to maximize compression efficiency across codecs. This configuration leads to significantly extended encoding times, and, since some tests only use a single quantization parameter (QP), and a very small number of sequences, this work concludes that a more exhaustive study is necessary to reach an unambiguous conclusion about the coding efficiency of these standards.

Nguyen et al. [15], in their comparison of VVenC (VVC), x265 (HEVC), and AV1, focus on balancing compression efficiency and encoding time. VVenC achieves a 37.6% BD-rate improvement at just 68% of the encoding time required by the encoder of HEVC (HM), demonstrating a significant trade-off advantage. Compared with VVenC, x265 requires approximately a 70% higher bit rate to achieve a similar quality within comparable encoding times, while AV1 achieves bit rate savings of up to 11.5% but requires longer encoding times than the slower presets of VVenC.

A recent comparative study by Lodi et al. [16] analyzes the performance of fast implementations of emerging video encoders relevant for real-time consumer systems, specifically VVEnC (VVC), XEVE (EVC), and SVT-AV1 (AV1), focusing on compression efficiency, encoding time, and scalability in multicore environments. Their results confirm VVEnc as the most efficient in terms of R-D performance, while SVT-AV1 achieves real-time encoding thanks to its multicore optimization. This work focuses on multi-core acceleration capabilities, using mainly low resolution sequences, without analyzing the comparative efficiency between generations of widely used codecs such as x264 or x265.

The above-mentioned studies on video coding standards do not contain an analysis of LCEVC, despite the growing attention it is receiving due to its alternative approach of enhancing existing codecs rather than replacing them. This omission is significant, as LCEVC offers a unique balance between compression efficiency and computational complexity, which could make it a strong candidate for various real-world applications. Moreover, a common limitation in these studies is their reliance on reference encoders, which, while useful for benchmarking, have execution times that are far from practical in real deployment scenarios. In some cases, optimized encoders are included in the analysis, but they are often evaluated alongside reference encoders without clear differentiation. This mixing of results makes it challenging to assess the true performance gains of optimized implementations and, consequently, to derive meaningful insights into the practical benefits of each codec.

One of the first studies of LCEVC was published in 2020 by Meardi et al. [17]. The study demonstrated that LCEVC enhanced AVC, HEVC, and VVC, achieving average BD-rate reductions of 27.56% and 2.37% for AVC and HEVC, respectively, but showing a 20.69% increase when used with VVC. Regarding computational performance, the encoding time of LCEVC ranged between 30% and 50% of the encoding time required by the anchors AVC and HEVC, depending on resolution, while the decoding time ranged from 60% to 95% of the decoding time of the anchors. Although the study highlights the efficiency of LCEVC in terms of computational requirements, no encoding or decoding time results were reported for VVC. This underscores the importance of evaluating the current performance of LCEVC, especially in comparison with emerging formats such as EVC, in order to assess its evolution and applicability in contemporary encoding scenarios.

A recent study performed in 2023 by Battista et al. [18] evaluates the performance of LCEVC across multiple objective and subjective metrics, and uses BD-rate to measure coding efficiency. The results show that LCEVC achieves reductions of approximately

TABLE 1. Encoding goals and typical use cases of the evaluated codecs.

ENCODER	ENCODING GOALS	TYPICAL USE CASES
V-Nova LCEVC SDK (LCEVC)	Enhances base codecs with a lightweight enhancement layer for improved efficiency and low complexity.	Low-latency streaming, bandwidth-constrained networks, devices with limited processing power.
SVT-AV1 (AV1)	High compression efficiency designed for modern internet video delivery.	Web streaming (YouTube, Netflix), browser playback, OTT services requiring wide device support.
XEVE (EVC)	Balances compression performance with flexible licensing (Baseline: royalty-free, Main: higher quality).	Broadcasters, online video platforms, enterprises seeking licensing flexibility.
VVenC (VVC)	Maximizes compression for UHD (4K/8K), HDR, and immersive formats with advanced coding tools.	High-end broadcasting, UHD Blu-ray, VR/AR, next-gen distribution (e.g., over 5G).
x265 (HEVC)	Provides significant bit rate savings over AVC while supporting UHD and HDR content.	UHD streaming, video conferencing, OTT services, high-quality storage.
x264 (AVC)	Efficient compression with maximum compatibility across devices and platforms.	Legacy devices, live streaming, video conferencing, widespread online video.

40% with AVC, 30% with HEVC, and 15% with both EVC and VVC for similar visual quality levels. In the study, a new methodology based on the average of the polynomial model of R-D curves was applied. However, processing time measurements are not included in this work, and these are crucial for the application of LCEVC in time-sensitive scenarios.

A recent evaluation by Chubach et al. [19] investigated the performance of LCEVC using the LTM-5.4.1 implementation combined with the HEVC and VVC reference encoders (HM and VTM) under JVET Common Test Conditions for 4K content. Their study focused on BD-rate using PSNR metrics and included informal subjective testing, concluding that LCEVC does not provide significant visual benefits when used with VVC at high resolutions. This conclusion differs from the findings of our study when LCEVC is used with x264. However, it is consistent with the conclusions reported in [19] when LCEVC is used with x265.

Beyond purely algorithmic and standard-oriented comparisons, recent research has increasingly emphasized the role of video codecs within consumer electronics ecosystems, where practical deployment constraints are as relevant as compression efficiency. In particular, OTT streaming services, smart TVs, mobile devices, and interactive applications such as cloud gaming and real-time video communication require codecs that balance rate–distortion performance with encoding and decoding complexity, latency, and energy consumption. A recent study performed by Hamidouche et al. [20], provides a detailed examination of VVC tools and their implications for real consumer devices and use cases (e.g., smart TVs and mobile receivers). Prior work has further highlighted that the computational complexity of video encoders has a direct impact not only on performance, but also on energy consumption and environmental sustainability, which are increasingly relevant considerations for consumer devices and large-scale video delivery infrastructures [21]. In particular, the energy consumption and associated carbon emissions of modern software video encoders have been shown to vary significantly across codecs and configurations, reinforcing the importance of complexity-aware evaluations in consumer-oriented scenarios [22]

Finally, enhancement-layer approaches such as LCEVC have attracted attention as a means to improve compression efficiency while preserving backward compatibility with legacy consumer devices, thereby facilitating incremental adoption in heterogeneous consumer environments [23].

Despite these advances, existing studies often analyze compression efficiency, perceptual quality, or computational complexity in isolation, or rely on reference software that is not representative of real consumer deployments. This motivates the comprehensive evaluation presented in this work, which jointly analyzes rate–distortion performance and runtime complexity using practical, consumer-relevant encoder implementations.

TEST CONDITIONS AND METRICS

In this section, we describe the methodology used to perform an objective and reproducible comparative performance evaluation of the video coding standards and corresponding practical Open-Source codecs under study.The chosen experimental environment is derived from the Verification Test Report on the Compression

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Performance of LCEVC [24], as specified in April 2021 at the 134th MPEG meeting for LCEVC, thus ensuring full adherence to the official LCEVC development specifications. The purpose of that verification test was to confirm that the target coding efficiency for the LCEVC standard had been met, reducing bit rate at a similar level of objective quality relative to a single-layer video codec such as AVC, HEVC, EVC, or VVC. While an in-depth analysis of the MPEG Verification Tests results is beyond the scope of this paper, a summary of the operational points used for the test and the conclusions are reported in [18]. The methodology described in that report is used in this paper to perform the comparative study, but with practical encoder implementations of each standard, with the aim of analyzing whether the same conclusions can be reached using an R-D/complexity analysis.

Test Conditions and Configurations

The test set comprises eight standard dynamic range (SDR) sequences, selected from the datasets provided in [24] and [25]. These include four UHD (3840×2160) sequences: *DrivingPOVLogo*, *BoxeLogo*, *BodeMuseum*, and *TiergartenParkway*, as well as four HD (1920×1080) sequences: *TrafficLogo*, *Starcraft*, *OberbaumSpree*, and *QuadrigaTree*. All original video sequences are progressively scanned and use 4:2:0 chroma subsampling with 10 bits per sample bit depth, and they have a duration of 10 seconds. The eight selected sequences exhibit heterogeneous characteristics aimed at ensuring a comprehensive and representative evaluation of codec performance. The dataset comprises natural content with overlaid banners and logos, computer-generated material with static graphical elements, as well as natural scenes characterized by high spatial detail, diverse textures, and varying degrees of motion. Furthermore, the inclusion of urban and outdoor scenarios with different camera dynamics provides greater variability, thereby enabling a more rigorous assessment of codec robustness across a wide spectrum of content types

Regarding the versions of the video encoders under study, the following ones were considered:

- V-Nova LCEVC SDK v3.10.6 (LCEVC) using x264 and x265 as base layer.
- XEVE v0.4.3 (EVC) using Main and Baseline profiles.
- VVenC v1.11.1 (VVC).
- SVT-AV1 v2.3.0-110 (AV1).
- x265 vFFmpeg 6.1 “Heaviside” (HEVC).
- x264 vFFmpeg 6.1 “Heaviside” (AVC).

All the encoders under study provide different presets, making it possible to trade off encoding time against compression-efficiency performance. Selecting fair and consistent encoding conditions across multiple encoders is a complex task, particularly given the wide range of configuration parameters unique to each one. To ensure comparability while maintaining clarity and feasibility, we opted to use the “medium” preset for all codecs. This preset represents a balanced trade-off between encoding speed and compression efficiency and is commonly available across all tested implementations. While not necessarily optimal for each codec, it provides a standardized and practical baseline for comparative analysis.

As all the encoders are compliant with the standard they are implementing, the same methodology as specified in [24] has been employed to derive the quantization step-sizes in our evaluation. All the experiments in this evaluation follow a random-access configuration, using a large group-of-pictures (GOP) size with an I-frame every 2 seconds, since this is an appropriate value to obtain larger VMAF and VMAF-NEG scores, as demonstrated in previous studies [26]. Table 2 provides a detailed overview of the parameters used for each encoder.

To avoid bias due to the I/O overhead, the time required to write the reconstructed YUV files was measured and excluded from the encoding/decoding time. Additionally, quality metrics were computed as a separate post-processing step on the decoder side, ensuring that these computations did not impact the encoding or decoding performance results.

Metrics

The R-D/complexity analysis presented in this paper has been evaluated in terms of the encoder or decoder run time (ERT/DRT) factor and R-D performance. The ERT or DRT factor was computed following Equation (1), where $\text{Enc. or Dec. Time}_{\text{test}}$ and $\text{Enc. or Dec. Time}_{\text{reference}}$ represent the encoding/decoding times of the evaluated encoder or decoder and the baseline encoder or decoder, respectively.

$$\text{ERT/DRT} = \frac{\text{Enc/Dec Time}_{\text{test}}}{\text{Enc/Dec Time}_{\text{reference}}} \tag{1}$$

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TABLE 2. Encoder and parameter settings. The parameter settings include values in braces to indicate that the parameter varies across different experiments, while other parameters maintain the same value for all of them.

ENCODER	PARAMETER SETTINGS
x264	ffmpeg -f {sequence} -pix_fmt yuv420p10le -s:v {resolution} -r {fps} -i {sequence} -c:v libx264 -qp {qp} -preset medium -g 120 -tune psnr -flags +psnr {output}
x265	ffmpeg -f {sequence} -pix_fmt yuv420p10le -s:v {resolution} -r {fps} -i {sequence} -c:v libx265 -qp {qp} -preset medium -g 120 -tune psnr -flags +psnr {output}
V-Nova LCEVC SDK (x264)	ffmpeg -f {sequence} -pix_fmt yuv420p10le -s:v {resolution} -r {fps} -i {sequence} -c:v lcevc_h264 -base_encoder x264 -qp {qp} -b:v 0k -g 120 -eil_params ”tune=psnr;lcevc_tune=psnr;lcevc_preset=1;preset=medium;rc_pcrf={qp};rc_pcrf_gop_length=120;threads=1” {output}
V-Nova LCEVC SDK (x265)	ffmpeg -f {sequence} -pix_fmt yuv420p10le -s:v {resolution} -r {fps} -i {sequence} -c:v lcevc_hevc -base_encoder x265 -qp {qp} -preset medium -b:v 0k -g 120 -eil_params ”tune=psnr;lcevc_tune=psnr;lcevc_preset=1;rc_pcrf={qp};rc_pcrf_gop_length=120” -threads 1 {output}
XEVE (Base)	xeve_app -i {sequence} -w {resolution[0]} -h {resolution[1]} -d 10 -z {fps} -v 3 --preset medium --qp {qp} --profile baseline --threads 1 -I 128 --tune psnr -o {output}
XEVE (Main)	xeve_app -i {sequence} -w {resolution[0]} -h {resolution[1]} -d 10 -z {fps} -v 3 --preset medium --qp {qp} --profile main --threads 1 -I 128 --tune psnr -o {output}
VVenC	vvencapp -i {sequence} -s {resolution} -c yuv420_10 -r {fps} --preset medium --qp {qp} -ip 128 -t 1 -o {output}
SVT-AV1	ffmpeg -f {sequence} -pix_fmt yuv420p10le -s:v {resolution} -r {fps} -i {sequence} -c:v libsvtav1 -preset 6 -qp {qp} -threads 1 -g 120 {output}

With regards to the R-D performance, the most widely-used objective metric is the Peak Signal-to-Noise Ratio (PSNR). This metric is easy to calculate and provides a rough indication of quality differences. However, its lower correlation with visual scores limits its applicability in modern video quality assessment. In 2016, the strengths of multiple metrics were combined into the VMAF metric, introduced by Netflix [27]. VMAF produces quality scores by taking into account both quantization artifacts (such as blockiness) and scaling artifacts (such as blurriness from upscaling). VMAF uses a scale from 0 to 100, which is easy to interpret and maps intuitively to Mean Opinion Scores (MOS), ranging from poor to excellent video quality. Due to its advantages and open-source availability [28], VMAF has become a de facto standard in consumer video delivery pipelines, enabling quality optimization aligned with end-user experience rather than purely signal-based fidelity. However, it should be noted that, since VMAF is designed to predict the subjective video quality as perceived by end users, it may yield higher scores in the presence of enhancement filters. This is particularly relevant when interpreting the results obtained for LCEVC, as it applies several enhancement filters as part of the decoding process. To mitigate this effect, in this study we also employ a variant of VMAF known as VMAF-NEG [29], which has been specifically designed to address this issue. VMAF-NEG extends the original VMAF metric by penalizing enhancement-related artifacts that may artificially increase quality scores. In particular, it introduces negative features to counterbalance the influence of enhancement filters, ensuring that the metric better reflects true perceptual quality rather than improvements yielded solely by post-processing. In this study, VMAF, and VMAF-NEG version 2.3.0 with model version 0.6.1 has been used.

After performing the objective quality tests to obtain the four VMAF and VMAF-NEG values for the four QPs used, the relative R-D performance of the different encoders under study, in terms of bit rate savings for the same quality range, can be computed by applying the BD-rate methodology. The BD-rate metric is a more formal, numbers-only analysis, typically used for codec comparisons. The metric essentially computes the bit rate reduction for the equivalent perceptual quality of one codec with respect to the other. This method is designed to calculate the average difference in bit rate between two R-D curves, where interpolation with a third-degree polynomial was recommended. The method, originally used for the interpolation of bit rate expressed as a function of PSNR, can be extended to a generic metric such as VMAF and VMAF-NEG [18], as used in our tests. In our comparative study, a positive BD-rate means the encoded bit rate using the test codec under study is higher than the bit rate obtained with the reference codec, and thus that is denoted as the penalty in terms of bit rate.

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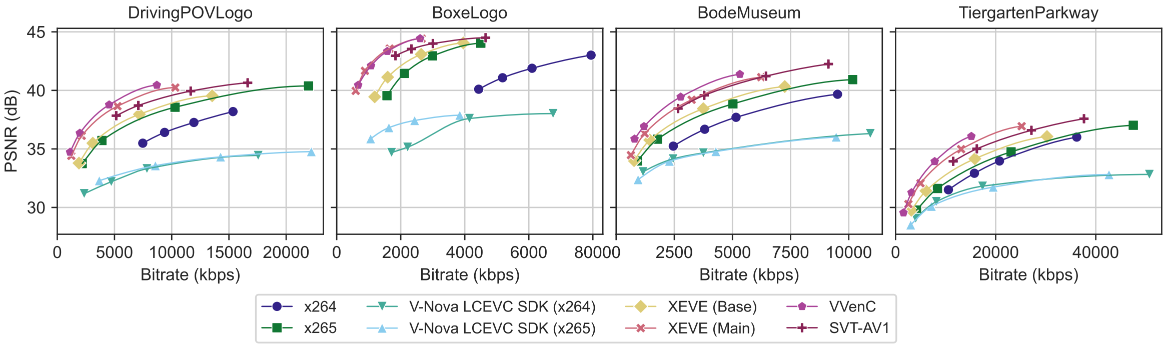
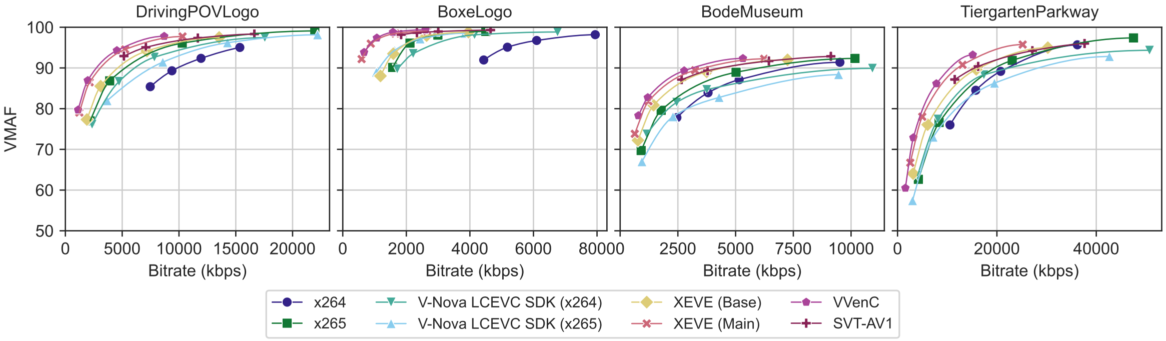
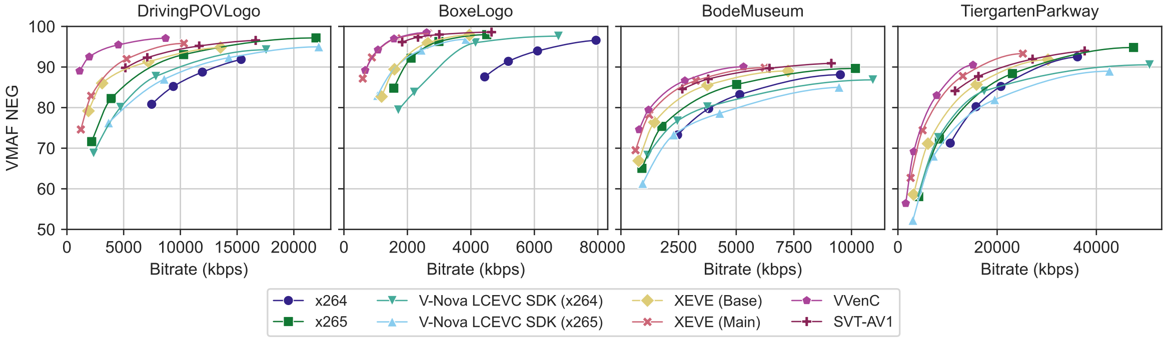


(a) PSNR



(b) VMAF



(c) VMAF NEG

FIGURE 1. Rate-distortion curves obtained by the encoders tested for the UHD sequences.

RESULTS

In this section, we provide a comprehensive comparative evaluation of the six practical video codecs under study. The tests were carried out on a hardware platform consisting of 37 nodes. Each node consists of 16 GB of main memory and an Intel® Xeon® E5-2630L v3 CPU, which supports AVX2, SSE4.2, and FMA3 instruction sets, with 8 physical cores running at 1.80 GHz with Turbo Boost disabled to ensure reproducibility. While this processor does not reflect the most recent advancements in hardware (e.g., AVX-512, heterogeneous compute units), it provides a stable and controlled environment for assessing relative codec performance. Each execution was performed using a single processor thread with the default compilation flags provided by the developers of the encoders. Analyzing the scalability of the different encoders is beyond the scope of this study and would be far from trivial, as each encoder employs different techniques to leverage the multiple cores available on modern processors. These parallelization strategies can significantly improve execution times but may also have a considerable impact on R-D performance, making a fair comparison even more complex. The single-

TABLE 3. UHD Sequences (BD-rate VMAF). Results indicate that VVenC is the best-performing encoder.

Ref Test	x264	x265	V-Nova LCEVC SDK (x264)	V-Nova LCEVC SDK (x265)	XEVE (Baseline)	XEVE (Main)	VVenC	SVT-AV1
x264	X	79.76%	47.03%	49.78%	105.25%	256.90%	283.64%	86.14%
x265	-38.55%	X	-14.40%	-16.43%	21.94%	90.45%	110.75%	36.21%
V-Nova LCEVC SDK (x264)	-27.23%	17.98%	X	-3.58%	43.62%	130.83%	157.62%	96.86%
V-Nova LCEVC SDK (x265)	-14,87%	25,49%	11.14%	X	57.08%	142.69%	174.80%	109.26%
XEVE (Baseline)	-49.66%	-17.31%	-29.65%	-30,52%	X	60.78%	76.25%	20.84%
XEVE (Main)	-65.48%	-46.37%	-54.54%	-58.15%	-34.79%	X	12.06%	-19.18%
VVenC	-69.27%	-52.00%	-59.69%	-62.60%	-41.34%	-10.73%	X	-31.05%
SVT-AV1	-56.44%	-25.42%	-46.50%	-49.81%	-14.94%	23.88%	45.67%	X

TABLE 4. UHD Sequences (BD-rate VMAF-NEG). Results indicate that VVenC is the best-performing encoder.

Ref Test	x264	x265	V-Nova LCEVC SDK (x264)	V-Nova LCEVC SDK (x265)	XEVE (Baseline)	XEVE (Main)	VVenC	SVT-AV1
x264	X	78.28%	32.64%	43.01%	80.46%	263.65%	440.22%	154.53%
x265	-38.95%	X	-21.65%	-19.33%	28.73%	96.91%	173.22%	45.66%
V-Nova LCEVC SDK (x264)	-21.43%	30.22%	X	5.07%	69.16%	163.14%	296.15%	126.21%
V-Nova LCEVC SDK (x265)	-12.90%	30.52%	4.97%	X	73.22%	162.61%	309.73%	136.85%
XEVE (Baseline)	-52.44%	-21.73%	-39.32%	-36.11%	X	56.48%	144.50%	28.14%
XEVE (Main)	-67.49%	-48.49%	-59.97%	-61.21%	-33.40%	X	52.71%	-18.18%
VVenC	-74.81%	-59.93%	-69.58%	-69.74%	-51.94%	-22.82%	X	-36.92%
SVT-AV1	-55.14%	-30.54%	-54.00%	-55.56%	-21.33%	22.85%	154.53%	X

threaded execution ensures fairness and consistency in the comparison.

Fig. 1 shows the R–D curves using the PSNR metric (top), the VMAF metric (middle), and the VMAF-NEG metric (bottom) obtained by each of the encoders under study. For each metric, the curves corresponding to the four representative UHD sequences are presented, while HD sequences are not shown due to space constraints. Points located closer to the top-left corner represent better coding efficiency results.

Fig. 1a shows the R-D curves using the PSNR metric. It is important to note that the PSNR is not well-suited to accurately reflecting the performance of LCEVC, since it does not correlate visual scores in comparison with VMAF and VMAF-NEG. This limitation is also evident in the results we obtained, where PSNR tends to underestimate the perceptual improvements introduced by V-Nova LCEVC SDK. For this reason, we have prioritized VMAF and VMAF-NEG as more reliable and perceptually-aligned metrics to ensure a fairer and more meaningful comparison across all evaluated codecs.

Fig. 1b and Fig. 1c show the R-D curves using the VMAF and VMAF-NEG metrics, respectively. The figures allow us to rank the codecs independently of the sequence, and this ranking is fully aligned with the order in which the codecs were introduced. The one furthest from the top-left corner (and thus the least efficient) is x264, followed by x265, XEVE (Base), SVT-AV1, XEVE (Main), and finally VVenC. However, the combined performance of the base and enhancement layers achieved by the LCEVC-based codec leads to improved efficiency when V-Nova LCEVC SDK is applied over x264, especially when low bitrates are used. In contrast, when combined with x265, V-Nova LCEVC SDK does not attain the same coding efficiency at quarter resolution as that achieved by the x265 anchor encoder operating at full resolution, regardless of the bitrates used. Finally, it is worth highlighting that when comparing the V-Nova LCEVC SDK curves with those of the base encoder, they tend to intersect. This indicates that at low QPs (i.e., high bitrates) V-Nova LCEVC SDK may struggle to outperform the base encoder, whereas at high QPs (i.e., low bitrates) V-Nova LCEVC SDK provides its greatest benefit.

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TABLE 5. HD Sequences (BD-rate VMAF). Results indicate that VVenC is the best-performing encoder.

Test \ Ref	x264	x265	V-Nova LCEVC SDK (x264)	V-Nova LCEVC SDK (x265)	XEVE (Baseline)	XEVE (Main)	VVenC	SVT-AV1
x264	X	62.67%	38.80%	25.34.%	102.47%	198.36%	209.05%	74.78%
x265	-33.20%	X	-15.28%	-27.34%	29.27%	84.24%	98.42%	40.11%
V-Nova LCEVC SDK (x264)	-24.49%	22.29%	X	-10.21.%	58.80%	136.49%	175.07%	104.48%
V-Nova LCEVC SDK (x265)	-10.28%	38.36%	15.36%	X	85.22%	171.20%	213.45%	117.40%
XEVE (Baseline)	-48.94%	-19.48%	-35.60%	-42.52%	X	46.50%	59.56%	16.65%
XEVE (Main)	-63.84%	-45.13%	-57.02%	-62.23%	-30.77%	X	11.87%	-19.31%
VVenC	-65.53%	-48.73%	-62.96%	-66.73%	-36.82%	-10.38%	X	-28.09%
SVT-AV1	-65.76%	-26.80%	-63.51%	-65.93%	-10.08%	26.06%	40.99%	X

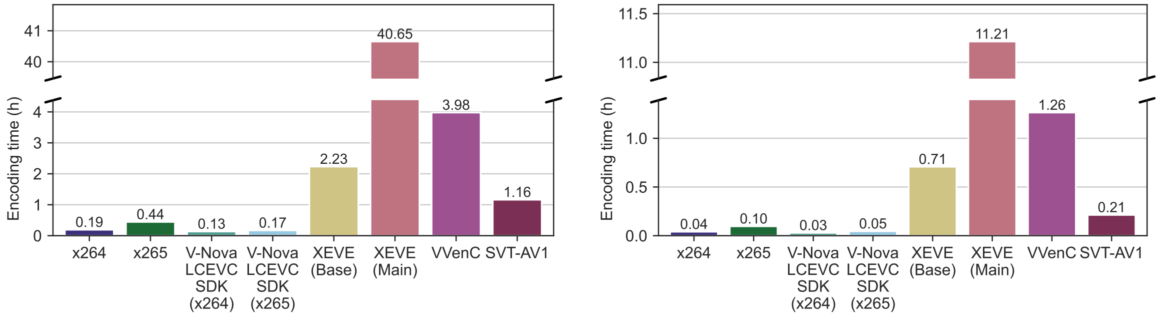
TABLE 6. HD Sequences (BD-rate VMAF-NEG). Results indicate that VVenC is the best-performing encoder.

Test \ Ref	x264	x265	V-Nova LCEVC SDK (x264)	V-Nova LCEVC SDK (x265)	XEVE (Baseline)	XEVE (Main)	VVenC	SVT-AV1
x264	X	62.39%	19.27%	19.93%	100.22%	205.40%	220.84%	89.13%
x265	-34.47%	X	-25.96%	30.29%	25.26%	88.52%	106.51%	49.56%
V-Nova LCEVC SDK (x264)	-14.18%	39.12%	X	0.15%	75.35%	172.44%	214.17.%	108.84%
V-Nova LCEVC SDK (x265)	-8.77%	44.34%	4.53%	X	87.11%	190.87%	246.43%	144.93%
XEVE (Baseline)	-48.49%	-18.81%	-42.96.%	-44.42%	X	53.03%	69.77%	25.70%
XEVE (Main)	-65.34%	-46.70%	-63.12%	-64.96%	-34.29%	X	12.94%	-17.11%
VVenC	-67.40%	-50.84%	-67.95%	-69.98%	-40.98%	-11.07%	X	-26.53%
SVT-AV1	-71.17%	-31.41%	-76.99%	-70.34%	-19.35%	21.95%	36.87%	X

The R-D curves allow a qualitative assessment of encoder performance, but a more analytical and objective comparison is necessary. In this regard, Tables 3 and 5 provide the average coding performances of all the codecs under study using the BD-rate VMAF for UHD and HD video sequences, respectively. In addition, Tables 4 and 6 present the corresponding results for the VMAF-NEG metric. First of all, the results show that the V-Nova LCEVC SDK combined with x264 achieves some bit rate savings compared with its base codec, namely x264 used alone at full resolution. Nevertheless, this improvement is less pronounced when assessed with the VMAF-NEG metric, which is much less sensitive to the sharpening effects introduced by LCEVC during the upsampling process. In contrast, when combined with x265, the LCEVC integration fails to achieve the same coding efficiency as the base encoder operating at full resolution. Additionally, the comparative results in Tables 3 to 6 highlight clear differences in coding efficiency across the evaluated encoders. VVenC consistently demonstrates the best overall performance, achieving the highest bitrate reductions relative to the rest of the encoders. Meanwhile, SVT-AV1 offers a balanced trade-off, outperforming x264, x265 and XEVE (Baseline profile) in efficiency while not reaching the compression levels of VVenC and XEVE (Main profile).

With regards to the computational requirements, the encoding time analysis presented in Fig. 2, which reports the average values across all the test sequences used, reveals significant differences between the tested codecs. V-Nova LCEVC SDK, when combined with either x264 or x265, consistently achieves the lowest encoding times, confirming its role as a low-complexity enhancement encoder. In contrast, XEVE in its Main profile is by far the most computationally demanding codec, with an ERT of 10,21 for UHD sequences and an ERT of 8,89 for HD sequences, with respect to VVenC, making it unfeasible for real-time applications. VVenC and SVT-AV1 exhibit intermediate encoding times, offering a balance between efficiency and complexity.

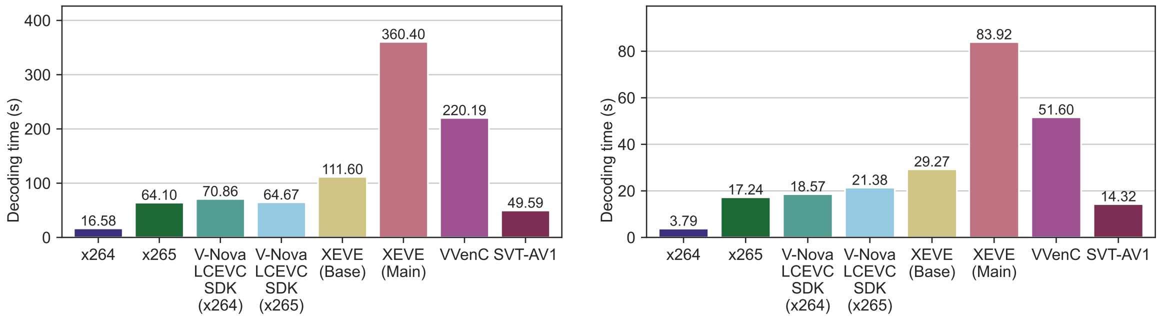
On the other hand, the decoding time analysis presented in Fig. 3 indicates that x264 consistently achieves the lowest complexity, confirming its suitability for scenarios with limited computational resources.



(a) UHD sequences

(b) HD sequences

FIGURE 2. Encoding times of the codecs tested. The charts show that V-Nova LCEVC SDK offers the lowest encoding time, while XEVE (Main) is the most computationally demanding codec.



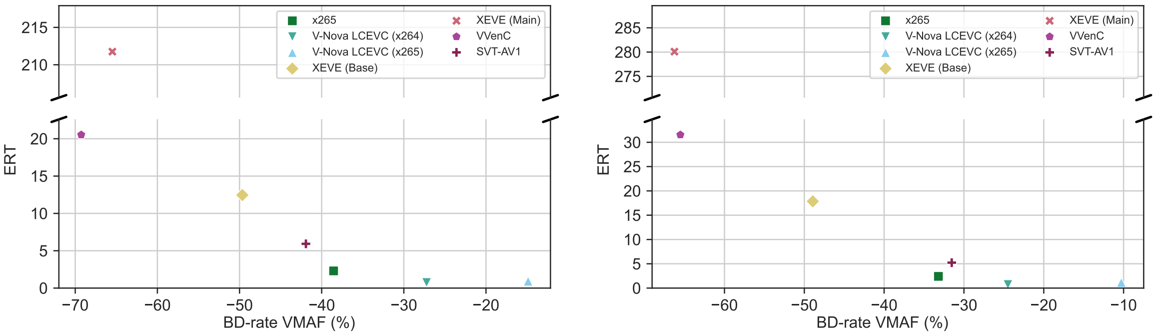
(a) UHD sequences

(b) HD sequences

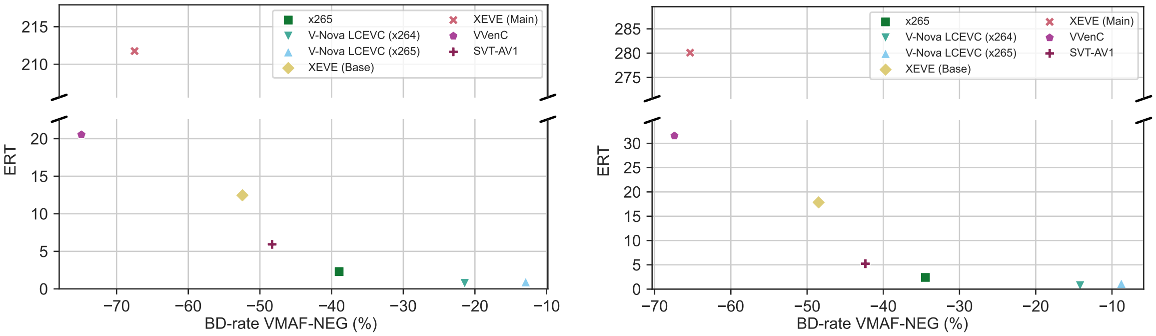
FIGURE 3. Decoding times of the codecs tested. The charts show that x264 offers the lowest decoding time, while XEVE (Main) is the most computationally demanding codec. The charts also highlight that V-Nova LCEVC SDK introduces a significant decoding overhead on top of the base layer.

At the opposite extreme, XEVE (Main) exhibits the highest decoding times, with a DRT of 1,63 for UHD sequences and a DRT of 1,82 for HD sequences, with respect to VVenC, highlighting its heavy computational demands. V-Nova LCEVC SDK, while offering benefits as a low-complexity enhancement layer during encoding, introduces a noticeable overhead at the decoding stage compared with its base codecs (x264 and x265). These findings underline the importance of considering both encoding and decoding performance when assessing codec practicality for real-world deployment scenarios.

To conclude this evaluation, Fig. 4 shows the relationship between BD-rate, using both VMAF (top) and VMAF-NEG (bottom), and encoding time using x264 as reference (point 0 , 0). This representation helps to put the impact of both factors into perspective. It should be noted that the efficiency-complexity trade-off of a codec is highly dependent on the preset selected, and different presets than the ones chosen for this evaluation could yield different results. When using the medium preset, SVT-AV1 emerges as a strong contender for internet-based video delivery and real-time applications, for which speed is critical. It achieves significant improvements with regards to older encoders, except when compared with x265 at HD resolution, for which it obtains a slightly poorer performance. Moreover, these improvements come at the cost of only a slight increase in encoder runtime. For practical deployments, the specific VVenC (VVC) and XEVE (Main) presets tested in this study come with significantly high encoding costs, making them challenging for real-time applications with current hardware. It is worth noting, however, that due to the superior compression efficiency of the VVC and EVC standards, even their faster presets (not evaluated here) are likely to achieve higher compression than older-generation codecs at similar encoding complexities.



(a) UHD Sequences (b) HD Sequences



(c) UHD Sequences (d) HD Sequences

FIGURE 4. Comparison of BD-rate using VMAF (top) and VMAF-NEG (bottom) versus ERT relative to x264 for UHD (left) and HD (right) sequences.

Meanwhile, V-Nova LCEVC SDK is the fastest when using both types of base layer, but its coding efficiency remains below that of the other encoders, with the exception of x264.

IN-DEPTH ANALYSIS OF V-NOVA LCEVC SDK

In this section, we aim to characterize the behavior of V-Nova LCEVC SDK by assessing the quality improvement provided by its enhancement layer. Specifically, we compare the quality of fully-decoded LCEVC bitstreams against that obtained when decoding only the base layer. This allows us to quantify the contribution of the enhancement layer to the overall coding performance. The evaluation was carried out using BD-rate VMAF and BD-rate VMAF-NEG as objective metrics, as these provide a comprehensive view of the quality gains across different aspects of perceptual and signal fidelity. In addition, we also analyzed the bitstream composition by quantifying the percentage of the total coded bitrate allocated to the enhancement layer.

The results in Tables 7 and 8 demonstrate that LCEVC's enhancement layer consistently improves perceptual quality. This is evidenced by the strongly negative BD-rate values for VMAF and VMAF-NEG across nearly all the test sequences for both the x264 and x265 base layers. As expected after the previous analysis, the improvements are more pronounced when using the VMAF metric. However, an exception arises for two sequences when using x265 as the base layer, where the V-Nova LCEVC SDK does not outperform the base codec. This phenomenon occurs when the enhancement layer introduces an excessive number of bits to the specific content of those sequences, which may have been less suitable for the type of enhancement provided by LCEVC.

To analyze the enhancement layer contribution in the bitstream, the last column of Tables 7 and 8 shows its impact with respect to the total bitstream. Note that values are averaged over the four QPs used to obtain the BD-rate results. When using x264 as base layer, it is highly efficient, requiring only a small fraction of the total bits (0.27% to 10.65%) to achieve significant

TABLE 7. Performance of V-Nova LCEVC SDK (x264) over the upscaled version of the base layer in terms of BD-rate VMAF and BD-rate VMAF-NEG, and relative size of its enhancement layer.

Res.	Sequence	BD-rate VMAF	BD-rate VMAF-NEG	Enhancement layer size
HD	QuadrigaTree	-25.10%	-12.74%	0.27%
	OberbaumSpree	-33.86%	-15.63%	8.45%
	TrafficHDLogo	-38.51%	-31.32%	10.65%
	Starcraft	-28.40%	-19.70%	8.44%
UHD	DrivingPOVLogo	-27.32%	-18.06%	5.99%
	BoxeLogo	-27.39%	-19.73%	8.13%
	BodeMuseum	-38.31%	-24.10%	7.83%
	TiergartenParkway	-20.38%	-10.52%	8.75%

TABLE 8. Performance of V-Nova LCEVC SDK (x265) over the upscaled version of the base layer in terms of BD-rate VMAF and BD-rate VMAF-NEG, and relative size of its enhancement layer.

Res.	Sequence	BD-rate VMAF	BD-rate VMAF-NEG	Enhancement layer size
HD	QuadrigaTree	-17.76%	-5.71%	12.85%
	OberbaumSpree	0.50%	15.75%	35.85%
	TrafficHDLogo	-34.89%	-33.17%	29.42%
	Starcraft	-21.08%	-41.35%	39.01%
UHD	DrivingPOVLogo	-25.84%	-25.54%	27.73%
	BoxeLogo	-13.87%	-35.33%	28.60%
	BodeMuseum	6.96%	19.53%	47.41%
	TiergartenParkway	-11.62%	-1.56%	12.04%

VMAF gains. However, with x265, the enhancement layer size is larger (12.04% to 47.41%). In most cases, this investment yields strong perceptual returns. However, in sequences such as OberbaumSpree and BodeMuseum, where the enhancement layer consumes over 35% of the bitstream, the VMAF gains diminish or become negative. This suggests that for complex content, an inefficient base layer can force the enhancement layer to work excessively, reducing its overall coding efficiency.

CONCLUSIONS

In this paper, we have presented a comprehensive comparative performance evaluation of six practical software implementations of recent video standards/coding specifications: x264 (AVC), x265 (HEVC), SVT-AV1 (AV1) VVenC (VVC), XEVE (EVC), and V-Nova LCEVC SDK (LCEVC). The study has focused on analyzing the trade-offs between compression efficiency, measured in terms of R-D (PSNR, VMAF and VMAF-NEG), BD-rate VMAF, and BD-rate VMAF-NEG, and computational complexity assessed by the encoder/decoder runtime, for high-resolution (UHD and HD) 10-bit consumer applications with a random-access configuration.

The results demonstrate that the V-Nova LCEVC SDK, when combined with x264, achieves noticeable bitrate savings compared with the base codec, although this improvement is less evident under the VMAF-NEG metric due to its reduced sensitivity to sharpening. In contrast, when combined with x265, LCEVC does not reach the coding efficiency of the base encoder operating at full resolution. Beyond coding efficiency, the findings also demonstrate that while the V-Nova LCEVC SDK provides clear benefits as a low-complexity enhancement layer during encoding, it introduces an additional overhead at the decoding stage compared with its base codecs. This highlights the need to jointly assess encoding and decoding performance when evaluating codec suitability for real-world applications. Nevertheless, an important advantage is that the bitstream always retains a decodable base layer (e.g., AVC/H.264 or HEVC/H.265), which ensures interoperability across heterogeneous devices, even when the enhancement layer is not supported. This incremental compatibility may ease adoption in environments where full hardware support for emerging codecs is not yet widespread.

In contrast, VVenC demonstrated the best performance in terms of BD-rate VMAF and BD-rate VMAF-NEG, achieving the highest coding efficiency among the tested codecs. However, this superior compression efficiency comes with a high computational cost. Similarly, XEVE, particularly in its Main profile, exhibited the highest encoder/decoder runtime, rendering it potentially unfeasible for real-time applications despite its relatively good compression performance, which is similar to VVenC.

Finally, SVT-AV1 delivers high compression efficiency, significantly outperforming older codecs such as x264 and x265. While not reaching the absolute best R-D of VVenC or XEVE (Main), its much lower encoder/decoder runtime makes it a practical choice for internet-based video and real-time applications.

FUTURE LANDSCAPE

Future work will increasingly leverage machine learning to advance video compression capabilities. As the volume of online video content continues to grow exponentially with the rise of streaming, there is a critical need for AI-driven encoding techniques. Historically, traditional machine learning approaches laid the groundwork for intelligent compression; today, deep learning models, particularly neural network–based algorithms, offer the potential to push performance to unprecedented levels. By incorporating end-to-end neural architectures and data-driven optimization, next-generation codecs can achieve superior rate-distortion trade-offs, enhanced perceptual quality, and adaptive behavior tailored to diverse deployment scenarios. Consequently, integrating these advanced AI methods represents a promising direction for the future of video coding.

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