A VVC/H.266 Real-time Software Encoder for UHD Live Video Applications

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1. SUMMARY

Versatile Video Coding (VVC) is the newest video coding standard designed to significantly reduce the bitrate over its predecessor, High Efficiency Video Coding (HEVC), as well as to facilitate next-generation video applications.

Spin Digital has succeeded in developing a VVC real-time software encoder for Ultra HD (4K and 8K) live streaming and broadcasting. The version achieves, for 4K video, a 18% bitrate savings at equal quality compared to Spin Digital's HEVC real-time encoder, an industry-leading encoder for its high performance and compression efficiency. In the case of 8K video, the average bitrate reduction amounts to 27%.

As a result of extensive algorithmic and platform-related optimizations, the VVC encoder can process 4Kp60 and 8Kp30 10-bit HDR videos in real-time using a single server with a dual-socket CPU architecture. In the near future, through the use of advanced encoding algorithms and next-generation CPU architectures, new releases of the encoder will enable real-time 8Kp60 10-bit HDR encoding and higher compression efficiency.

Spin Digital's VVC encoder has been integrated into a live streaming framework that includes all the required components for live applications such as: input capture (SDI and IP), pre-processing filters, pre-analysis, advanced rate control, audio and video encoding, and HTTP and TS-over-IP streaming and broadcasting.

This document describes the implementation of the encoder and presents an evaluation of its compression efficiency and performance for 4K- and 8K-UHD live streaming applications. The encoder is evaluated with other software and hardware (GPU-based) encoders for UHD live applications. Results show that the new encoder achieves higher compression efficiency than other encoders while at the same time has the required performance for UHD real-time encoding.

2. INTRODUCTION: TRENDS IN LIVE MEDIA APPLICATIONS

In the first half of 2022, video traffic accounted for about 66% of the total share of Internet data traffic, which is a 24% increase over the first half of 2021 (Sandvine 2023). And nearly 20% of Internet video traffic is already live (Cisco 2018) (SkyQuest 2022). OTT live and on-demand services are becoming increasingly popular, forcing traditional TV broadcasters to also use the open Internet to boost viewership (Careless 2021) (SES 2022). In addition to professional created content, User-Generated Content (UGC) is being live-streamed on platforms such as YouTube and Facebook, generating significantly higher engagement rates (Bern 2019). Apart from TV and live video streaming, other live applications include gaming, video conferencing, virtual desktop, and video social networking. The Covid-19 pandemic has also changed the way in which people are interacting in private and professional life: there are more and more video conferencing sessions as well as more live events online. And these trends do not seem to change in the post-pandemic scenario (Wyman 2021).

The next generation of live applications is primarily focused on delivering higher quality video as well as immersive experiences that engage the end user more with the content. The 4K Ultra-High Definition (UHD) High Dynamic Range (HDR) format is becoming mainstream, 8K-UHD streaming and broadcasting is already a reality, 8K 360-/180-degree video is an accepted format for high-end live Virtual Reality (VR) streaming applications, and gaming sharing and virtual desktop applications are increasingly using UHD video resolutions

For these emerging live services, High Efficiency Video Coding (HEVC) represents the state-of-the-art codec for compressing video with lower data rates without sacrificing quality (Spin Digital 2020, Ultra HD Forum 2021). However, HEVC is reaching its maximum compression efficiency capacity. As a result, next-generation codecs are needed to make these enhanced applications more accessible.

Versatile Video Coding (VVC), or H.266, is the latest video coding standard that not only provides significantly higher compression efficiency than HEVC, but is also designed to enable efficient coding of different types of video, such as UHDTV (4K and 8K), VR/360-degree, and screen content. VVC also includes tools for more efficient encoding for adaptive bitrate streaming and scalable encoding. VVC coding solutions, especially for live streaming and broadcasting, will be essential in the near future to facilitate the development of next-generation multimedia applications.

3. THE VVC/H.266 STANDARD AND ITS APPLICATIONS

The VVC/H.266 standard was completed in July 2020 by the Joint Video Experts Team (JVET) of ISO and ITU (Bross et al. 2020). VVC represents the state-of-the-art in video coding providing 50% bitrate reduction with respect to its predecessor, HEVC/H.265, for the same visual quality. This level of compression gain is only possible at the expense of significant computational increase.

In the currently fragmented codec landscape, VVC competes with other coding standards including AV1 by the Alliance for Open Media (AOM), Low Complexity Enhancement Video Coding (LCEVC) and Essential Video Coding (EVC) by MPEG. Independent evaluations have shown that VVC can achieve higher compression efficiency than these other standards: e.g. 19.5% to 20.5% better than AV1 and 27.3% to 30.5% better than EVC for UHD video (Grois et al. 2021).

3.1. VVC TARGET APPLICATIONS

VVC not only produces higher compression than other standards, but is also designed to achieve more efficient coding of different types of content: including 2D regular camera content, screen content, and 360-degree video, and new-generation video formats including 4K- and 8K-UHD with HDR and VR/360°.

In addition, VVC includes new features to make Adaptive Bitrate (ABR) streaming services more efficient, as well as adding support for scalability coding scalability, a coding technique to compress video in multiple layers, each layer representing a different resolution or quality of the same video.

3.2. VVC ENCODERS: LIVE VS VOD

HEVC implementations already achieve the performance required to transmit 4K and 8K video live over the Internet as well as broadcast channels. Using latest-generation HEVC real-time encoders, the typical bitrates to produce broadcast-grade quality 4Kp60 video range from 10 to 40 Mbps (Ultra HD Forum 2022) and for 8Kp60 from 48 to 80 Mbps (Schwarz 2 2022). However, these encoding solutions have reached a point of diminishing returns for HEVC under real-time conditions, meaning that adding more computation will result in marginal compression gains.

In order to reduce the bandwidth beyond the capabilities of HEVC and, in this way, make UHD live services more accessible to the public, new-generation codecs are needed. Figure 1 shows a comparison of state-of-the-art performance optimised encoding implementations of AVC, HEVC, AV1, and VVC for 4K-UHD video in terms of compression efficiency and encoding complexity. Compression efficiency is measured as bitrate increase at equal quality referred to a baseline encoder, and encoding complexity is calculated as CPU utilisation time relative to that of a baseline encoder based on HEVC with a configuration that represents the best operational point for real-time applications.

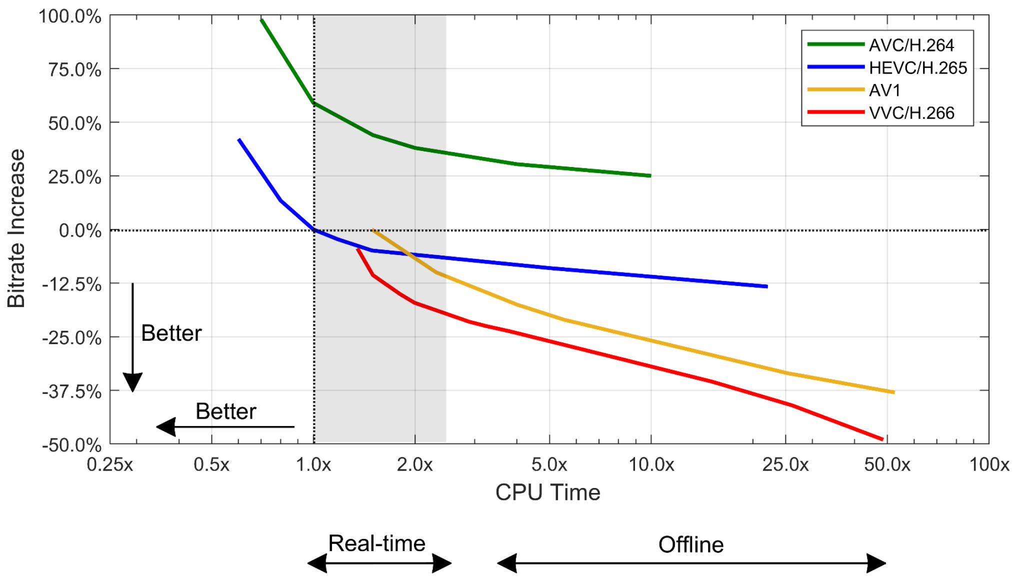

Figure 1: Video codecs (AVC, HEVC, AV1, and VVC) compression efficiency capabilities and encoding complexity. When a video codec reaches a point of diminishing returns the next generation codec offers the path for further compression gains.

The figure illustrates how the baseline HEVC encoder is able to process 4Kp60 video in real time, and with the same computational complexity has a much higher compression efficiency than AVC/H.264.

Beyond a relative complexity of 1.5x HEVC and AVC are no longer able to significantly increase compression efficiency. In contrast, AV1 and especially VVC implementations are able to significantly overcome the compression limits of HEVC at very high complexity. Finally, from a complexity higher than 25.0x, it is observed that VVC increases its compression efficiency advantage compared to AV1.

But not all quality-compression configurations are possible for real-time encoding. We suggest that the sweet spot is located between 1x to 2.5x the complexity of the baseline HEVC encoder. Beyond that point the encoders can be used for *offline* encoding applications such as Video-on-Demand (VoD). Figure 1 shows that an optimised VVC encoder is able to achieve up to 50% bitrate reduction compared to the baseline HEVC live encoder, but at the cost of 50 times the computational complexity.

4. SPIN DIGITAL'S VVC REAL-TIME ENCODER

Spin Digital has developed the first version of a high-quality and highly optimised VVC software encoder for UHD HDR live broadcast and streaming.

The encoder has been extensively optimised using:

- Advanced mode and partitioning decision algorithms aimed at improving compression efficiency while reducing VVC encoding complexity.
- SIMD processing using AVX2 and AVX-512 instructions.
- Scalable multithreading exploiting different levels of parallelism (wavefront,, frame, pipelining) for systems with hundreds of CPU cores.

With all these optimizations together, the new encoder enables real-time encoding of 4K at 60 fps and 8K at 30 fps video in 10-bit HDR using a dual-socket server with a total of 76 CPU cores.

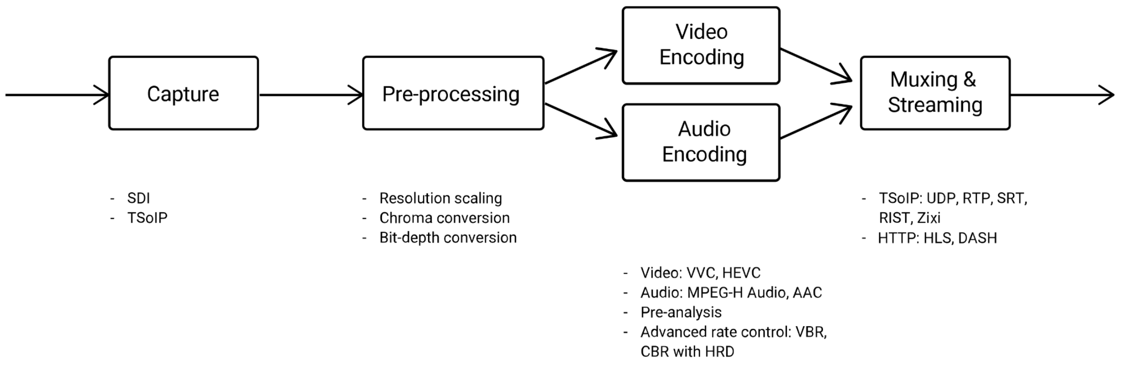

Figure 2: Key components of Spin Digital's VVC live encoder diagram

In order to obtain higher compression efficiency than HEVC with an affordable increase in CPU resources, VVC coding tools were analysed, selected and implemented according to their potential for compression, quality and real-time implementation. Spin Digital's VVC encoder includes major VVC tools such as enhanced block partitioning, new intra-prediction modes and tools, extended motion vector prediction and inter-prediction tools, large block-size transforms and better entropy coding, as well as deblocking, SAO and ALF in-loop filters.

In addition to the VVC standard tools, the encoder includes advanced rate control algorithms (VBR, and CBR with HRD model), pre-analysis, and perceptually optimised encoding.

The VVC encoder has been integrated into a complete application for live streaming and broadcasting (see Figure 2), and it is also available as a SDK module and as a FFmpeg plugin.

The application and SDK include and combine all the modules required for live streaming including: input capture with both SDI and IP interfaces, pre-processing (scaling, colour conversion, tone mapping), advanced rate control, core VVC (and HEVC) encoding, audio encoding (MPEG-H Audio, AAC), and streaming for HTTP (HLS, DASH) or Transport Stream over IP (TS-over-IP) delivery (UDP, RTP, SRT, RIST, Zixi).

5. ENCODER ASSESSMENT FOR 4K-UHD STREAMING AND BROADCASTING

The new Spin Digital VVC real-time encoder was assessed in terms of compression efficiency, encoding complexity, and multithreaded encoding speed. The results were also compared to five open-source software encoders and two GPU-based hardware encoders of different coding standards including H.264/AVC, H.265/HEVC, AV1, and VVC/H.266.

The encoders were configured assuming a **4K-UHD live streaming and broadcasting scenario**. This use case mainly requires that the rate control is enabled and that long Group-of-Picture (GOP) structures are used for maximum compression efficiency with frequent random access points (e.g. 1 to 3 seconds intra period).

A wide set of test video sequences have been selected that are representative of 4K-UHDTV content as well as long enough to stabilise the rate control.

5.1. VIDEO SEQUENCES

A total of 11 1-minute 4K video sequences representing the target use case were selected in these experiments (see Table 1). The test set includes camera footage, animation and videos with visual effects.

The video sequences were acquired from different providers including: Netflix (Xiph 2015, Netflix 2022), Poznan Supercomputing and Networking Center (PSNC) (Immersify 2018), Fraunhofer HHI (Fraunhofer HHIl 2022), and Unigine (Unigine 2017).

The master files were preprocessed using Spin Digital’s high-precision filters to generate a 4K-UHD broadcast distribution format, which is specified in Table 1.

A detailed description of the input sequences including the preprocessing operations applied to each sequence are described in a separated Annex ”Technical Data Sheet of the Test Video Sequences”.

Table 1: Technical specifications of the 4K-UHD distribution format

Parameters	4K-UHD distribution format
Resolution	3840x2160 pixels
Frame rate	24, 59.94, 60 fps
Chroma sampling	4:2:0
Bit-depth	10 bits
Transfer function and colour gamut	SDR: SDR, BT.709 HDR: PQ, BT.2020

Table 2 presents detailed information of the test sequences: producer, type of content, HDR and colour gamut formats, and Spatial Information (SI) and Temporal Information (TI) (ITU-R 2019). The obtained SI and TI values cover a wide spectrum of complexities, from low (Meridian, RollerCoaster) to high (SolLevante, TunnelFlag) SI and TI, demonstrating the heterogeneity in complexity of the selected sequences (Figure 3). More technical information about these videos is given in a separated appendix.

Table 2: Technical information of the test sequences: producer, type of content, format, SI, TI

	Producer	Type	Format	SI	TI
BasketballGame	Netflix	Footage	4Kp59.94 HDR	112.6 (med)	152.2 (med)
BerlinSeqs	Fraunh. HHI	Footage	4Kp60 HDR	172.2 (med)	63.6 (low)
DrivingPOV	Netflix	Footage	4Kp59.94 HDR	150.0 (med)	147.4 (med)
FollowCar	PSNC	Footage	4Kp59.94 SDR	201.9 (high)	111.8 (med)
MC2	PSNC	Footage	4Kp59.94 SDR	280.5 (high)	82.5 (low)
Meridian	Netflix	Footage & CGI	4Kp59.94 HDR	89.8 (low)	23.6 (low)
RollerCoaster	Netflix	Footage	4Kp59.94 HDR	92.3 (low)	84.9 (low)
SolLevante	Netflix	Animation	4Kp24 HDR	237.5 (high)	269.4 (high)
Superposition	Unigine	CGI	4Kp60 SDR	226.5 (high)	82.9 (low)
ToddlerFountain	Netflix	Footage	4Kp59.94 HDR	170.2 (med)	79.3 (low)
TunnelFlag	Netflix	Footage	4Kp59.94 SDR	211.6 (high)	206.8 (high)

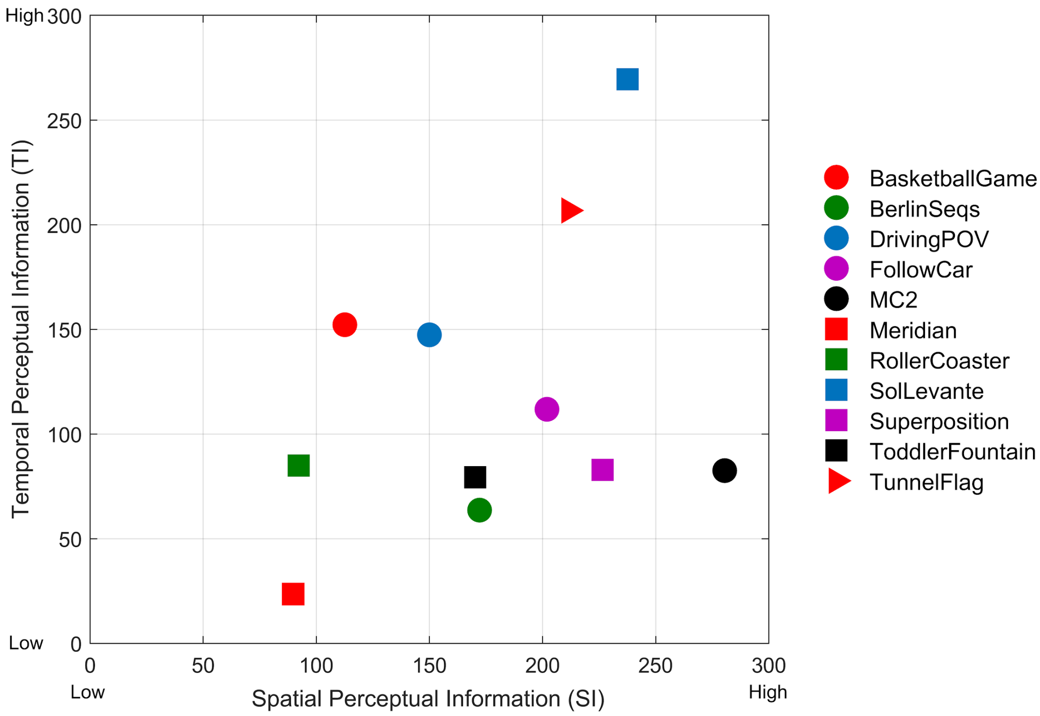

Figure 3: Spatial and Temporal Perceptual Information of the test sequences

5.2. VIDEO ENCODERS

Spin Digital's VVC encoder has been analysed together with other 8 encoders including open-source software and GPU-based (hardware encoders) covering a wide range of implementations and video coding standards from H.264/AVC to H.266/VVC.

The evaluated encoders are: one software AVC/H.264 encoder (x264); three HEVC software implementations (x265, SVT-HEVC, Spin Digital HEVC) and one GPU-based HEVC encoder (NVENC-HEVC); two AV1 encoders, one software-based (SVT-AV1) and one GPU-based (OneVPL-AV1); and two VVC software encoders (VVenC, Spin Digital VVC). A summary is presented in Table 3.

Spin Digital's HEVC and VVC encoders are part of a commercially available product called Spin Enc Live (Spin Digital 2022, Spin Digital 2023). For the sake of clarity, from now on these encoders will be called *Spin Digital HEVC and Spin Digital VVC respectively*.

Table 3: Encoders used for 4K compression efficiency and performance analysis

	Type	Standard	Company	Version	Release date	Reference/ repository
x264	SW	AVC	VideoLAN	r3094	Apr. 2022	(FFmpeg 2022)
x265	SW	HEVC	Multicore Ware	3.5	Apr. 2022	(FFmpeg 2022)
SVT-HEVC	SW	HEVC	Intel	1.5.1	June 2021	(Intel 2022)
NVENC-HEVC	HW	HEVC	Nvidia	12.0	Nov. 2022	(Nvidia 2022)
Spin Digital HEVC	SW	HEVC	Spin Digital	2.0	Jan. 2023	(Spin Digital 2023)
SVT-AV1	SW	AV1	Intel & Netflix	1.4.1	Dec. 2022	(Intel, Netflix 2022)
OneVPL-AV1	HW	AV1	Intel	2.8	Nov. 2022	(Intel 2 2022)
VVenC	SW	VVC	Fraunhofer HHI	1.7.0	Dec. 2022	(A. Wieck. 2022)
Spin Digital VVC	SW	VVC	Spin Digital	2.0	Feb. 2023	(Spin Digital 2023)

5.3. ENCODING SETTINGS

The video encoders were configured as similarly as possible assuming the 4K-UHD streaming and broadcast scenario. This use case typically requires random-access encoding mode (long GOP), open GOP, 1-second intra period, and Constant Bit Rate (CBR) rate control with a 1-second buffer size for the Hypothetical Reference Decoder (HRD) model. Some exceptions to this typical configuration are:

- The Variable Bit Rate (VBR) algorithm of SVT-AV1 was selected, since the CBR method is not supported in random-access mode;
- VBR was also selected in VVenC and, in addition, a buffer model is not included as VVenC does not support the HRD constraint.

In addition, the encoders were tuned to maximise the objective quality defined by the Peak Signal-to-Noise Ratio (PSNR) metric and, consequently, perceptual optimizations were disabled. Other parameters, such as GOP size, GOP structure, and lookahead window were kept at their default values.

The target bitrates were selected based on the recommendations given by the Ultra HD Forum for 4K HEVC final distribution (Ultra HD Forum 2021). In particular, for compression efficiency (BD-rate) analysis a range between 8 and 44 Mbps in steps of 4 Mbps was used. This range is wide enough to accurately compare different generations of encoders.

For each encoder several presets were selected in order to analyse different tradeoffs between quality and speed. As for NVENC-HEVC, this encoder includes, along with the encoding presets, the following tuning modes: high-quality (hq), low-latency (ll), and ultra low-latency (ull). In these experiments the high-quality mode was chosen.

5.4. COMPARISON METRICS

The video encoders were compared from the compression efficiency, encoding complexity, and performance points of view using BD-rate, CPU time and the encoding speed in frames per second, respectively.

Compression efficiency: BD-rate

The Bjontegaard Delta (BD)-rate method (Bjøntegaard 2001, Bjøntegaard 2008) was used to compute compression efficiency. Its goal is to compute the average bitrate increase produced by a test encoder referred to a baseline encoder at the same quality

Spin Digital's HEVC real-time encoder - Spin Digital HEVC - was selected as the baseline encoder. Four quality metrics used in the experiments were: PSNR, Perceptually Weighted PSNR (XPSNR) (Helmrich et al. 2020, Helmrich 2021), Multi-Scale Structural Similarity (MS-SSIM) (Wang, Simoncelli, and Bovik 2003), and Video Multi-method Assessment Function (VMAF) (Netflix 2021). The PSNR, XPSNR, and MS-SSIM metrics were calculated using the luma and chroma components.

Encoding complexity: CPU time

Encoding complexity was measured in terms of average CPU time (including both user-level and system-level CPU time) over the target bitrates during the encoding process, relative to a reference encoder (Spin Digital HEVC). Note that the CPU time is the accumulated time across all CPU cores, and can therefore be considered as *single-threaded encoding time*. This metric is only applicable to software encoders.

The platform used to run the encodings and quality metrics for BD-rate and CPU time computation is a server with the following components:

- CPU: 4x Intel Xeon Platinum 8176 CPU @ 2.10GHz (4x 28 cores)
- DRAM: 24x 16 GB DDR4 2666 MHz
- OS: Ubuntu 20.04

Encoding jobs were executed in parallel using the parallel job scheduling framework called *parallel* (Tange 2018). For the sake of a fair comparison, the number of encoding threads was set to 8 in the software encoders. An analysis of maximum encoding speed when using a high-performance multi-core CPU is described next.

Performance: average multithreaded encoding speed

The performance of the encoders was measured in terms of average multithreaded encoding speed. This measurement allowed us to determine the number of frames per second produced by the encoders running on a latest-generation multi-core platform when enabling the maximum encoding threads.

The average encoding speed provided by the encoding applications was taken instead of using the elapsed time facilitated by the Linux *time* command, as the former measures the performance devoted to encoding only, excluding the time consumed for memory allocation and other initialization steps at the beginning of the encoding.

The server specifications used to measure the speed performance of the encoders are listed below:

- CPU: Intel Xeon Platinum 8368@ 2.4 GHz (2x 38 cores)
- GPUs: Nvidia RTX 3070, Intel ARC A770
- DRAM: 16x 16 GB DDR4 3200 MHz
- OS: Red Hat 8.5

5.5. COMPRESSION EFFICIENCY AND ENCODING COMPLEXITY

The compression efficiency and encoding complexity of the new Spin Digital VVC encoder together with all the evaluated encoders is presented in Figures 4, 5, 6, and 7 for PSNR, XPSNR, MS-SSIM, and VMAF metrics respectively.

The reference encoder is ***Spin Digital HEVC - balanced***, where *balanced* is the preset that obtains the best tradeoff between compression efficiency and complexity for 4K.

For comparison purposes with the software encoders, the BD-rate results for the hardware encoders are plotted on the left side of the figures without CPU time information, since CPU time cannot be calculated in hardware encoders.

For the case of Spin Digital VVC - balanced, where the balanced preset represents a good compromise between compression efficiency and complexity for 4K video, the obtained BD-rate savings over Spin Digital HEVC - balanced ranges from 16.18% to 17.54% depending on the quality metric used, while requiring 65% more CPU resources.

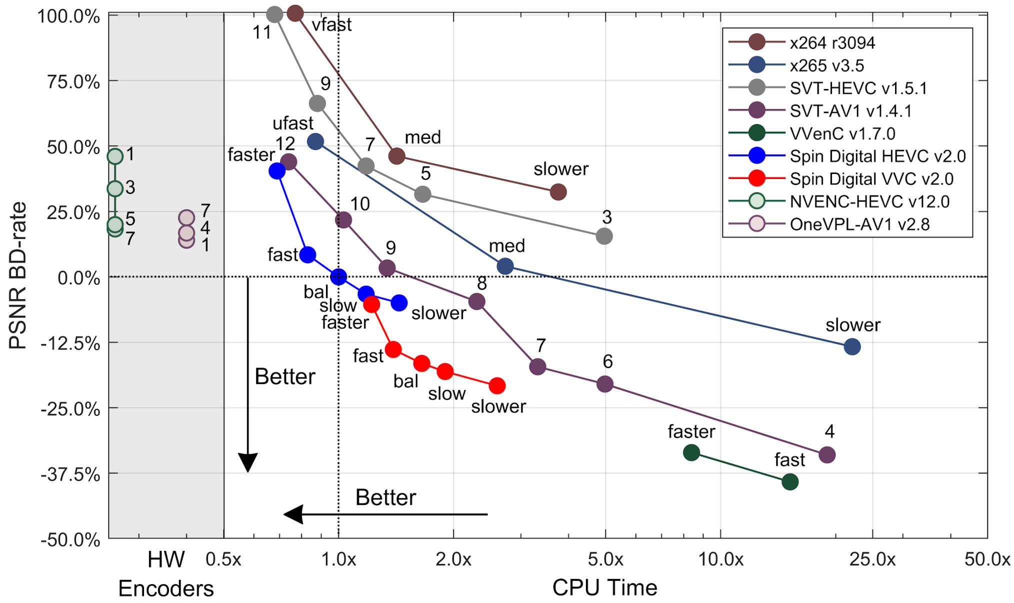

Figure 4: PSNR BD-Rate and CPU utilisation time for 4K video relative to Spin Digital HEVC for the encoders and presets under evaluation

When compared to an optimised HEVC encoder, Spin Digital's VVC encoder yields a BD-rate savings from 16.18% (MS-SSIM) to 17.54% (VMAF) at 1.65 times the computational complexity.

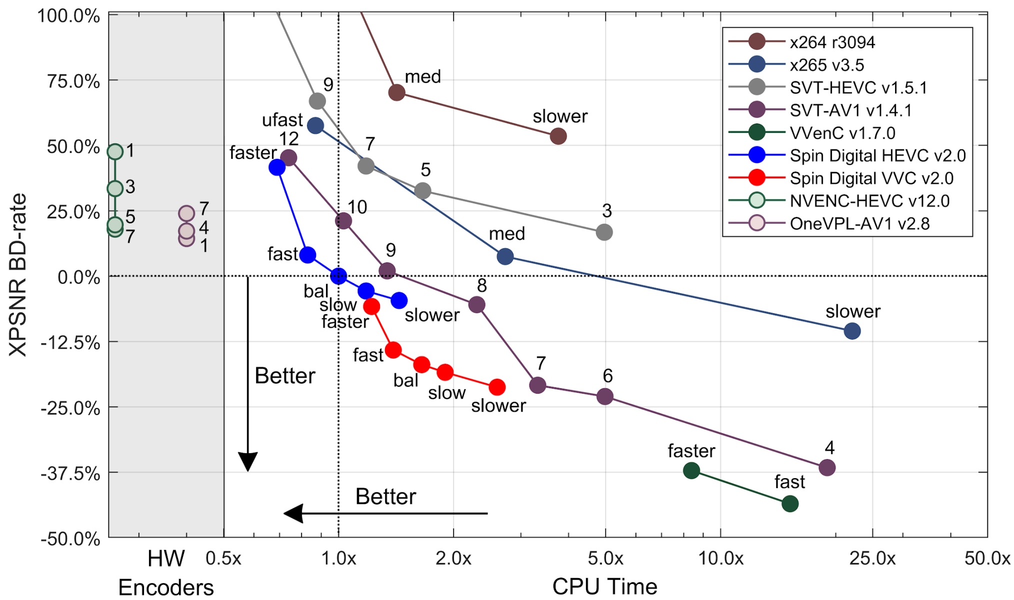

Figure 5: XPSNR BD-Rate and CPU utilisation time for 4K video relative to Spin Digital HEVC for the encoders and presets under evaluation

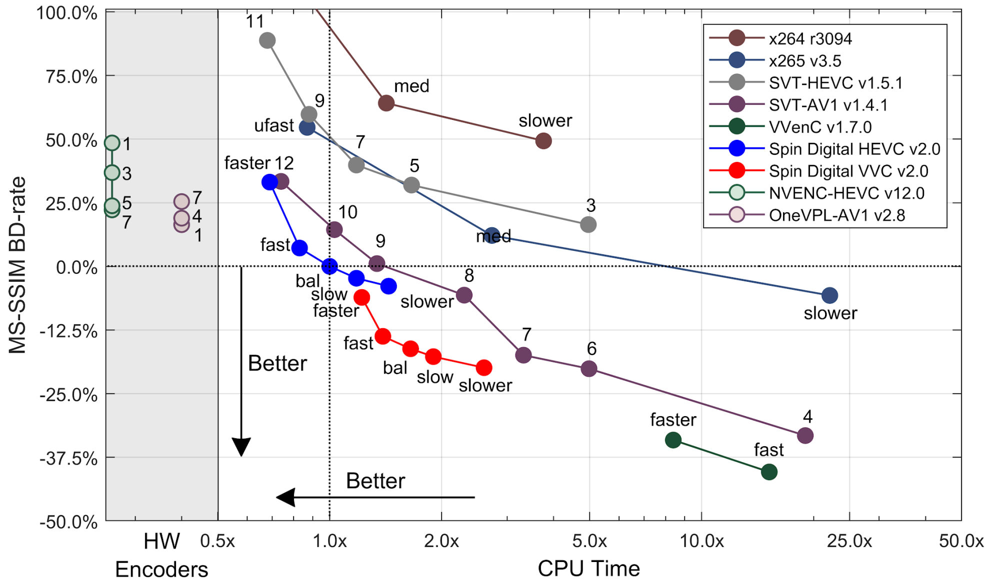

Figure 6: MS-SSIM BD-Rate and CPU utilisation time for 4K video relative to Spin Digital HEVC for the encoders and presets under evaluation

At similar compression efficiency, Spin Digital VVC is 50% less complex than SVT-AV1 (7) and significantly less complex than x265 (slower).

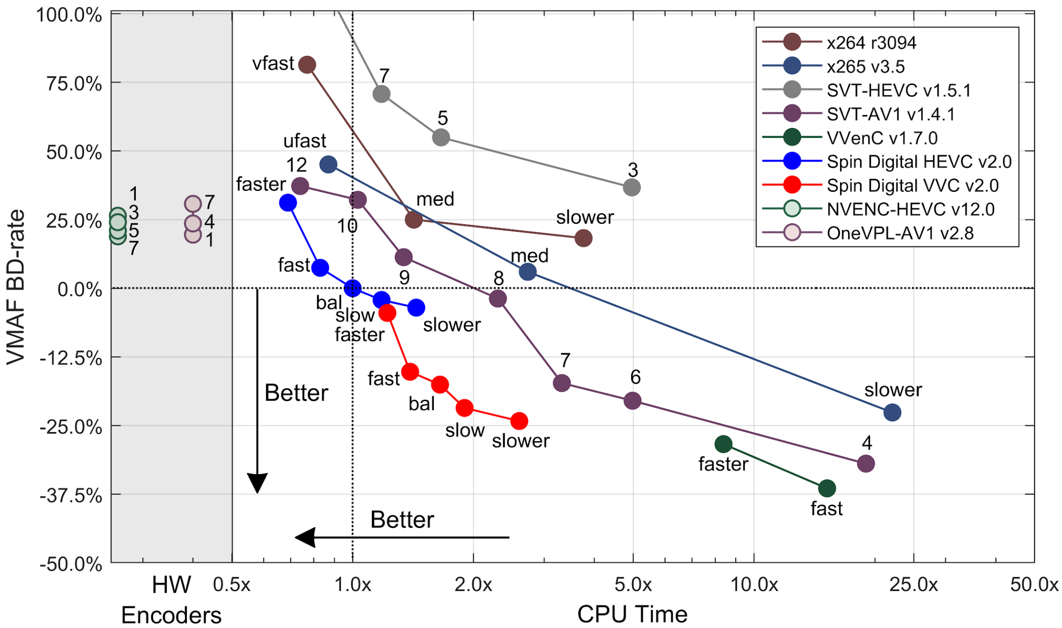

Figure 7: VMAF BD-Rate and CPU utilisation time for 4K video relative to Spin Digital HEVC for the encoders and presets under evaluation

When assuming comparable complexity, *Spin Digital VVC - balanced* achieves higher BD-rate gains than SVT-AV1 - 9, for example: -16.53% vs 3.39% (PSNR) or -17.54% vs 11.32% (VMAF).

Moreover, it is observed that the BD-rate reduction achieved by *Spin Digital VVC - balanced* is comparable to those of *SVT-AV1 - 7* and *x265 - slower*, but those encoding modes require 2.0 times and 13.4 times more computation, respectively.

It can also be seen that Spin Digital's encoders outperforms in compression efficiency the GPU-based hardware encoders. For example, the *NVENC-HEVC - 5* and *OneVPL-AV1 - 4* encoders which, as we will show later have the required performance for real-time 4Kp60, result in BD-rate increases between 17% to 23% relative to *Spin Digital HEVC - balanced*, and between 40% and 45% with respect to *Spin Digital VVC - balanced*.

The GPU-based hardware encoders produce, for 4K video, BD-rate increase of up to 45% with respect to Spin Digital VVC.

Table 4 reports the results in terms of BD-rate and CPU time for a narrower range of bitrates between 6 Mbps and 25 Mbps, which can be considered more realistic for 4K VVC or AV1 video. For the sake of simplicity, the results correspond to Spin Digital's HEVC and VVC encoders, SVT-AV1 - 9, and VVenC - faster.

Table 4: Results for 4K video in terms of BD-rate based on different quality metrics (PSNR, XPSNR, MS-SSIM, VMAF) and CPU time relative to Spin Digital HEVC for selected encoders and presets under evaluation. The bitrate range for BD-rate calculation is 6 Mbps to 25 Mbps

Encoder - preset	**PSNR BD-rate [%]**	**XPSNR BD-rate [%]**	**MS-SSIM BD-rate [%]**	**VMAF BD-rate [%]**	**CPU Time [times]**
SVT-AV1 v1.4.1 - 9	-0.02	-2.01	-2.66	6.20	1.43
VVenC v1.7.0 - faster	-32.22	-36.89	-35.43	-29.50	7.72
Spin Digital HEVC v2.0 - bal	0.00	0.00	0.00	0.00	1.00
Spin Digital VVC v2.0 - bal	-16.32	-16.64	-16.51	-16.20	1.53

As can be seen, the results for *Spin Digital VVC - balanced*, when using a range between 6 Mbps and 25 Mbps are similar to the results obtained using a larger range of bitrates (8 Mbps to 44 Mbps), which was needed for comparing multiple codec generations.

5.6. COMPRESSION EFFICIENCY PER SEQUENCE

Table 5 provides more detailed information about the BD-rate savings obtained by the new VVC encoder when compared to the HEVC baseline. According to these results, Spin Digital's VVC encoder achieves, with its balanced preset, an average bitrate reduction of 16.53% for the same PSNR, ranging from 11.88% to 26.89%, at the expense of 1.65 times the complexity of Spin Digital HEVC - balanced. If the VMAF metric is used, the VVC encoder achieves a 17.54% BD-rate reduction, going from 8.57% to 30.44%. When using other metrics, the encoder exhibits similar compression gains.

Table 5: BD-rate results for each 4K video sequence achieved by Spin Digital VVC - balanced referred to Spin Digital HEVC - balanced

Video Sequence	PSNR BD-rate [%]	XPSNR BD-rate [%]	MS-SSIM BD-rate [%]	VMAF BD-rate [%]
BasketballGame	-16.02	-16.52	-14.23	-15.91
BerlinSeqs	-11.88	-12.14	-10.23	-15.72
DrivingPOV	-17.89	-18.60	-17.43	-18.70
FollowCar	-26.89	-26.86	-26.71	-24.06
MC2	-11.94	-13.00	-10.50	-11.75
Meridian	-12.42	-13.36	-11.13	-18.08
RollerCoaster	-16.92	-17.51	-15.49	-16.86
SolLevante	-13.31	-14.52	-14.93	-13.84
Superposition	-18.84	-18.73	-18.17	-30.44
ToddlerFountain	-12.51	-12.39	-13.71	-8.57
TunnelFlag	-21.76	-21.27	-23.69	-16.82
Average	-16.53	-16.92	-16.18	-17.54

5.7. SELECTED QUALITY-BITRATE PLOTS

Unlike the BD-rate metric, which gives a single number representing the compression efficiency of an encoder in average over a range of bitrates, the quality-bitrate (rate-distortion) curves provide a better insight of the compression efficiency of the encoders for individual test sequences.

The following figures show the quality-bitrate curves based on PSNR, XPSNR, MS-SSIM, and VMAF for *DrivingPOV*, which is a representative sequence from the compression efficiency point of view. In order to reduce the number of encoders and presets displayed, only those that produce comparable complexities around 2.0x (from 1.0x to 3.0x) were included: x264 - medium, x265 - medium, SVT-HEVC - 5, SVT-AV1 - 9, Spin Digital HEVC - balanced (our reference), and Spin Digital VVC - balanced. Although VVenC has no preset falling in the specified range of complexity, VVenC - faster has also been included as a reference of VVC's potential in terms of compression efficiency. As for the hardware encoders, the presets that produce the highest quality were selected.

As can be observed, VVenC - faster achieves in general the highest quality at equal bitrate –but at the cost of 8.4x the complexity– followed by Spin Digital VVC and then by SVT-AV1 - 9.

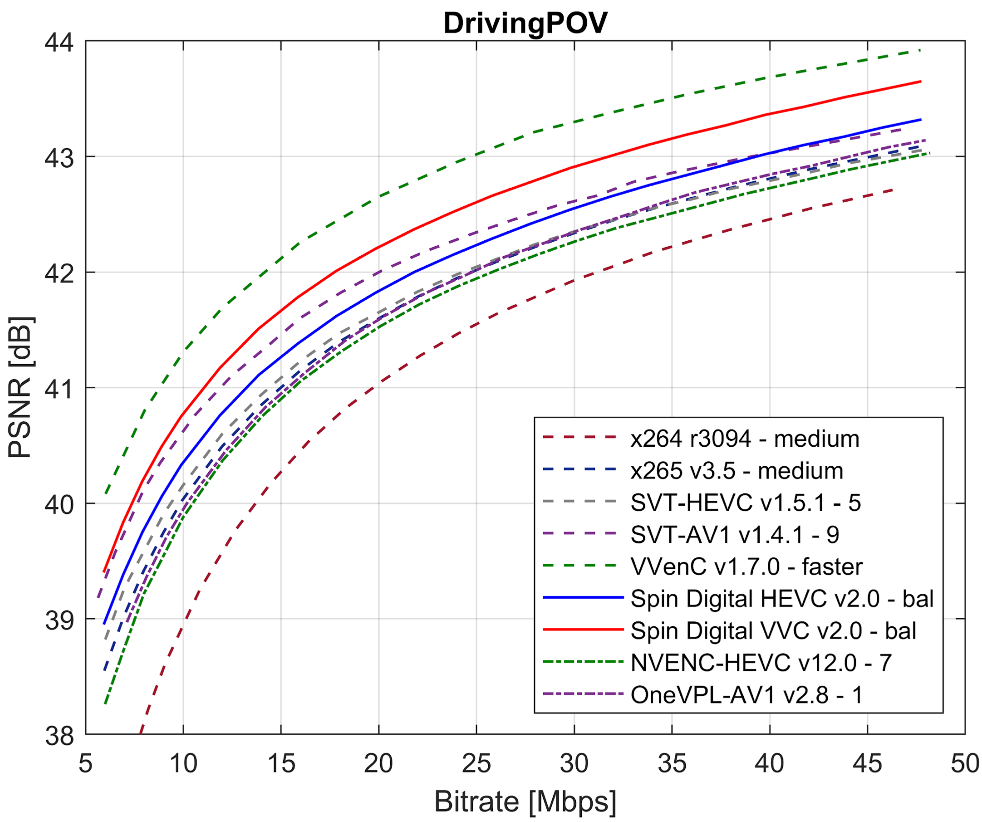

Figure 8: PSNR-bitrate curves for DrivingPOV

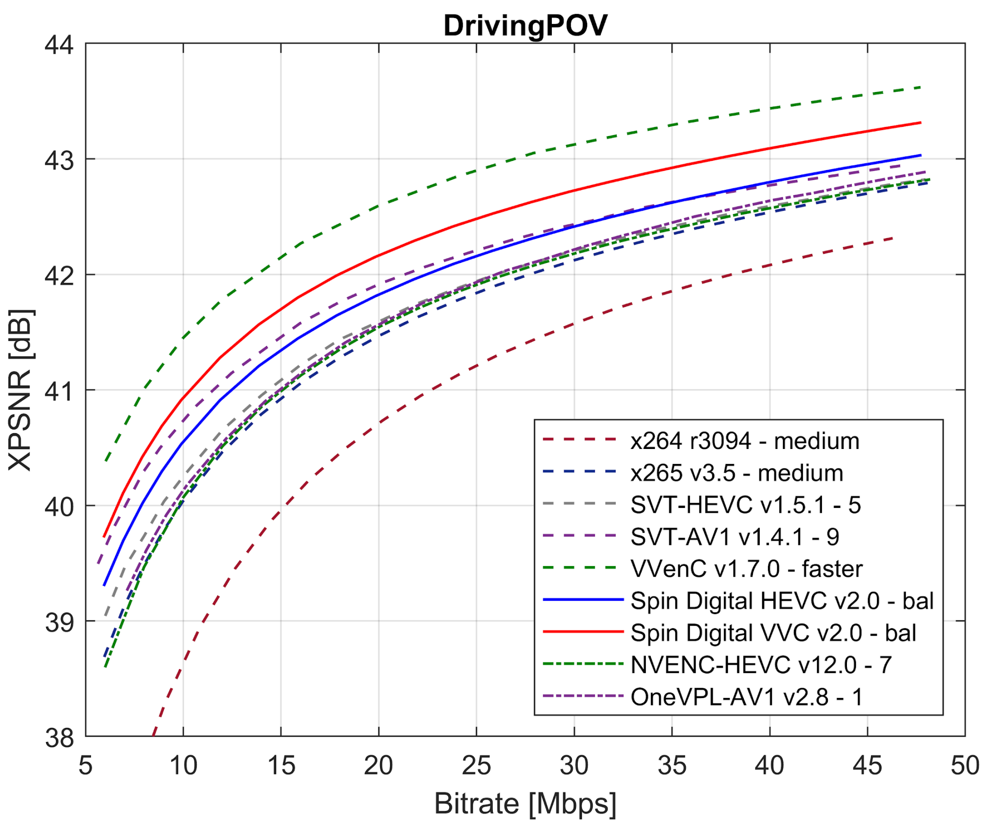

Figure 9: XPSNR-bitrate curves for DrivingPOV

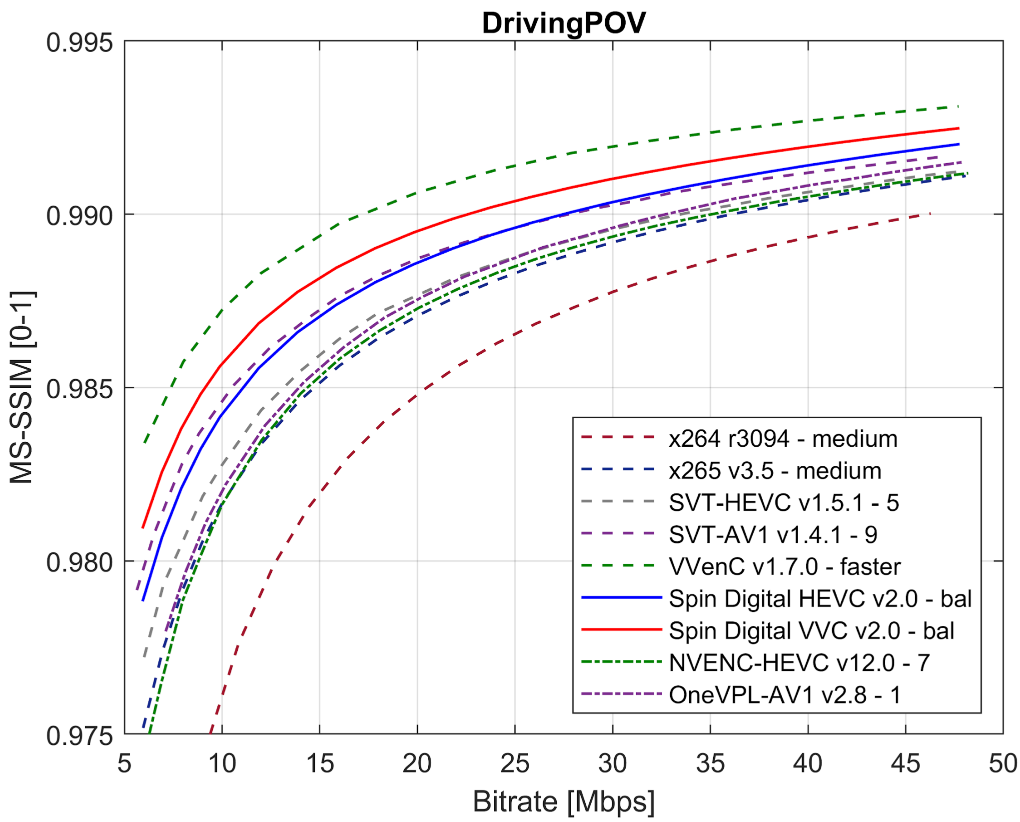

Figure 10: MS-SSIM-bitrate curves for DrivingPOV

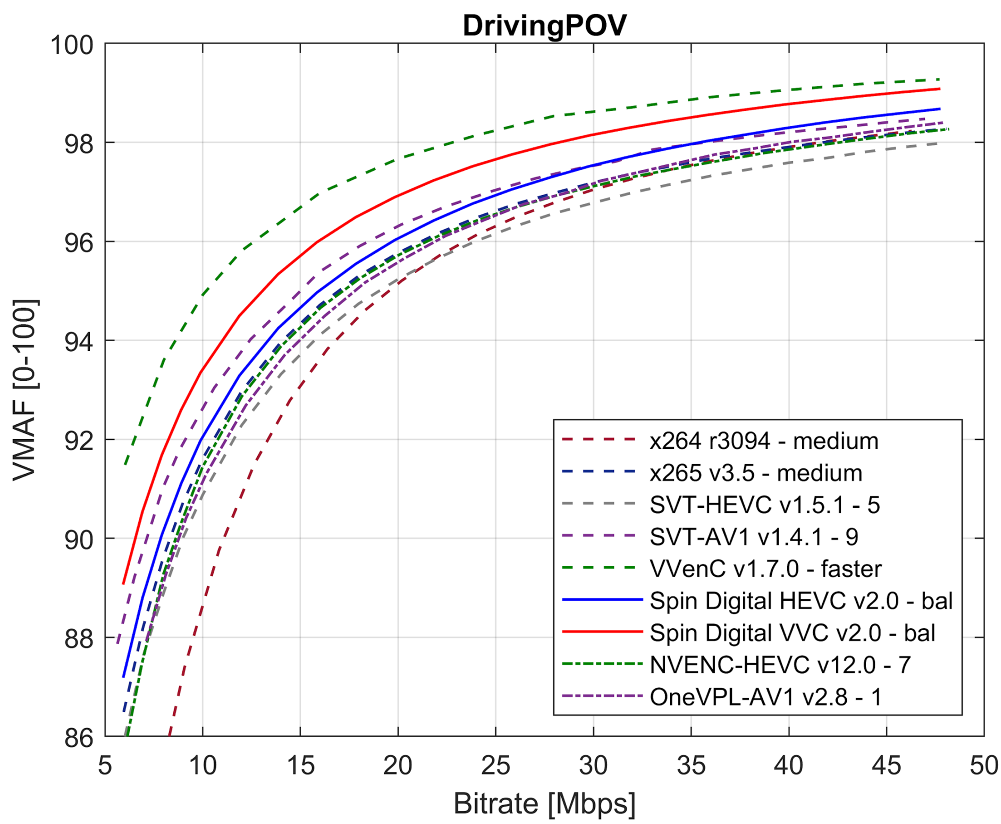

Figure 11: VMAF-bitrate curves for DrivingPOV

5.8. MULTITHREADED ENCODING SPEED

The performance of the encoders is measured on a server with two Intel Xeon Platinum 8368 CPUs (2x 38 cores) for the CPU-based software encoders, and two GPUs: Nvidia RTX3070 and Intel ARC A770 for the GPU-based hardware encoders. *DrivingPOV* was used in these experiments, being one of the most difficult sequences in the test set from an encoding speed point of view.

The criterion chosen to configure the encoders for performance tests was to select the bitrate such that all of them result in the same quality. A target PSNR of 41.5 dB was chosen to produce a very high quality that in turn results in a sufficiently high bitrate for benchmark purposes.

The software encoders were configured to enable the maximum number of threads for the target server. For the sake of a fair performance comparison, the hardware encoders were integrated into Spin Digital's encoding framework which is optimised for live applications. In order to reduce the impact of uncompressed input YUV file disk reading and output bitstream writing, the encoders were configured to use fast file read modes or encoding from memory and not to write the resulting bitstreams to the disk.

Figure 12 shows the encoding speed results for the bitrate required to obtain the same quality.

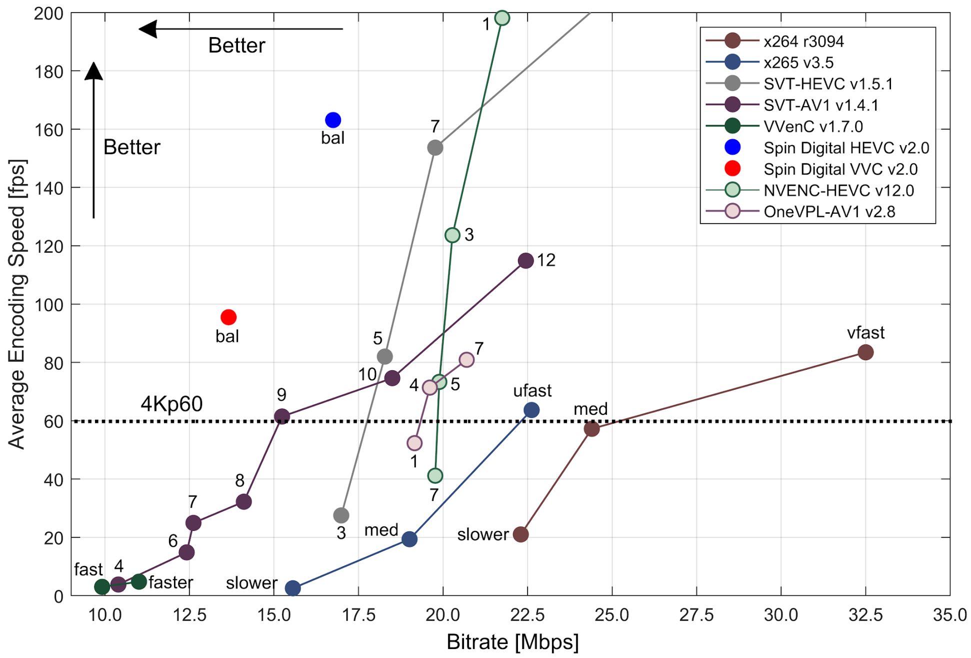

Figure 12: Actual bitrate for a PSNR of 41.5 dB and encoding speed produced by the encoders and presets when encoding DrivingPOV (4K 10-bit HDR) using two Intel Xeon Platinum 8368 CPUs (2x 38 cores), the RTX3070 GPU for NVENC, and the ARC A770 GPU for OneVPL

According to the results shown in Figure 12, both the VVC and HEVC real-time encoders developed by Spin Digital are able to attain average encoding speeds beyond real-time (60 fps), while producing the lowest bitrates under real-time conditions. These VVC and HEVC encoders operate, respectively, at 95.49 fps and 163.11 fps obtaining output bitrates of 13.66 Mbps and 16.75 Mbps for the same target quality.

With the exception of VVenC, which is not designed for live applications, the other encoders require fast presets to reach a performance comparable to Spin Digital VVC at its balanced preset, but at the cost of increasing the rate to achieve the same quality. For example, *SVT-HEVC - 5*, *SVT-AV1 - 10*, *NVENC-HEVC - 5*, and *OneVPL-AV1 - 4* produce, respectively, 33.8% (18.28 Mbps), 35.4% (18.50 Mbps), 45.6% (19.89 Mbps), and 43.6% (19.61 Mbps) more bitrate Spin Digital VVC.

Spin Digital’s VVC encoder achieves for 4K an average encoding speed beyond 60 fps (95.5 fps) while producing the lowest bitrate of all evaluated encoders under real-time conditions.

It is also noteworthy that the complexity when running at maximum speed in a multicore system is very different from the single-threaded complexity reported in Figure 4. In particular, it can be noticed that the parallel processing performance of Spin Digital VVC is more scalable than that of SVT-AV1. For example, the VVC encoder is 23% more complex than SVT-AV1 - 9 in single-threading mode (Table 4), but 55% faster in multithreading mode.

6. ENCODER ASSESSMENT FOR 8K-UHD BROADCASTING AND STREAMING

The VVC encoder developed by Spin Digital has also been assessed for 8K video in terms of compression efficiency (BD-rate), complexity (CPU time), and performance (multithreaded encoding speed).

6.1. TEST CONDITIONS

Video sequences

A total of eight 1-minute video sequences in 8K format (7680x4320 pixels, 50/59.94/60 fps, 10-bit, PQ/HLG with BT.2020 and SDR with BT.709) were used. Four of them have already been used for the 4K-UHD case, more specifically: *BerlinSeqs* (Fraunhofer HHI 2022), *FollowCar* and *MC2* (Immersify 2018), and *Superposition* (Unigine 2017). Additional sequences include: three footage clips from NHK Technologies called *Fuji*, *Haru*, and *Helicopter,* and one nature content from The Explorers called *Teaser 1* (The Explorers 2021).

The following table provides more information on the test sequences and, in the separated appendix, more details including the applied preprocessing operations are described.

Table 6: Technical information of the 8K sequences: producer, type of content, format, SI, TI

	Producer	Type	Format	SI	TI
BerlinSeqs	Fraunh. HHI	Footage	8Kp60 PQ	100.8 (med)	59.3 (low)
FollowCar	PSNC	Footage	8Kp59.94 SDR	150.8 (med)	113.3 (med)
Fuji	NHK Tech.	Timelapse	8Kp59.94 SDR	133.6 (med)	20.5 (low)
Haru	NHK Tech.	Footage	8Kp59.94 HLG	186.9 (high)	65.5 (low)
Helicopter	NHK Tech.	Footage	8Kp59.94 SDR	307.5 (high)	88.2 (low)
MC2	PSNC	Footage	8Kp59.94 SDR	187.2 (high)	86.1 (low)
Superposition	Unigine	CGI	8Kp60 SDR	153.4 (med)	92.1 (low)
Teaser1	The Explorers	Footage	8Kp50 PQ	101.6 (med)	52.7 (low)

Video encoders

Spin Digital VVC encoder was evaluated for 8K using Spin Digital HEVC as the baseline. Other encoders included in the analysis are: x265, SVT-HEVC, SVT-AV1, NVENC-HEVC, and OneVPL-AV1. Table 7 shows more information about all these encoders.

Table 7: Encoders used for 8K compression efficiency and performance analysis

	Type	Standard	Company	Version	Release date	Reference/ repository
x265	SW	HEVC	Multicore Ware	3.5	Apr. 2022	(FFmpeg 2022)
SVT-HEVC	SW	HEVC	Intel	1.5.1	June 2021	(Intel 2022)
NVENC-HEVC	HW	HEVC	Nvidia	12.0	Nov. 2022	(Nvidia 2022)
Spin Digital HEVC	SW	HEVC	Spin Digital	2.0	Jan. 2023	(Spin Digital 2023)
SVT-AV1	SW	AV1	Intel & Netflix	1.4.1	Dec. 2022	(Intel, Netflix 2022)
OneVPL-AV1	HW	AV1	Intel	2.8	Nov. 2022	(Intel 2 2022)
Spin Digital VVC	SW	VVC	Spin Digital	2.0	Feb. 2023	(Spin Digital 2023)

Encoding settings

The videos were encoded with the encoding settings for **live broadcasting and streaming** described in Section 5.3 and a bitrate range between 30 Mbps and 100 Mbps in steps of 10 Mbps.

Encoder presets

Spin Digital's VVC and HEVC encoders were configured with the *fast* preset, which is capable of achieving 8K real-time operation on a single server. Other encoders were configured with presets of similar quality or complexity.

6.2. COMPRESSION EFFICIENCY AND ENCODING COMPLEXITY

The results from the point of view of compression efficiency and complexity are summarised in Figures 13 to 16 using the PSNR, XPSNR, MS-SSIM, and VMAF metrics.

As can be observed, Spin Digital VVC achieves BD-rate savings with respect to Spin Digital HEVC of 22.29% (PSNR), 22.60% (XPSNR), 18.34% (MS-SSIM), and 27.22% (VMAF). This compression efficiency comes at the cost of 47% more encoding complexity.

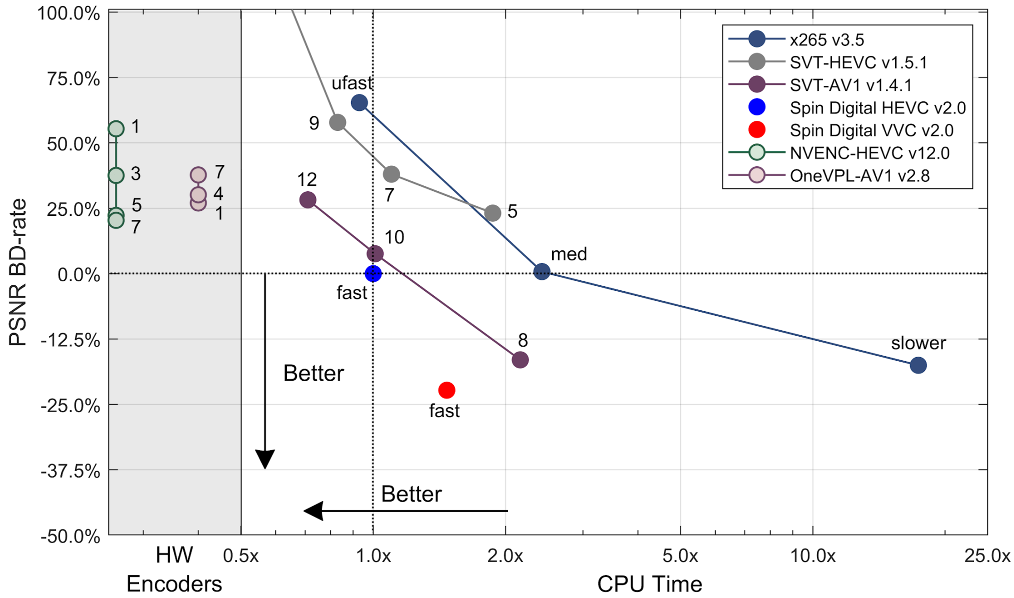

Figure 13: PSNR BD-Rate and CPU utilisation time for 8K video relative to Spin Digital HEVC for the encoders and presets under evaluation

Spin Digital VVC achieves a BD-rate reduction from 18.32% (MS-SSIM) up to 27.22% (VMAF) over Spin Digital HEVC at 1.47 times the computational complexity.

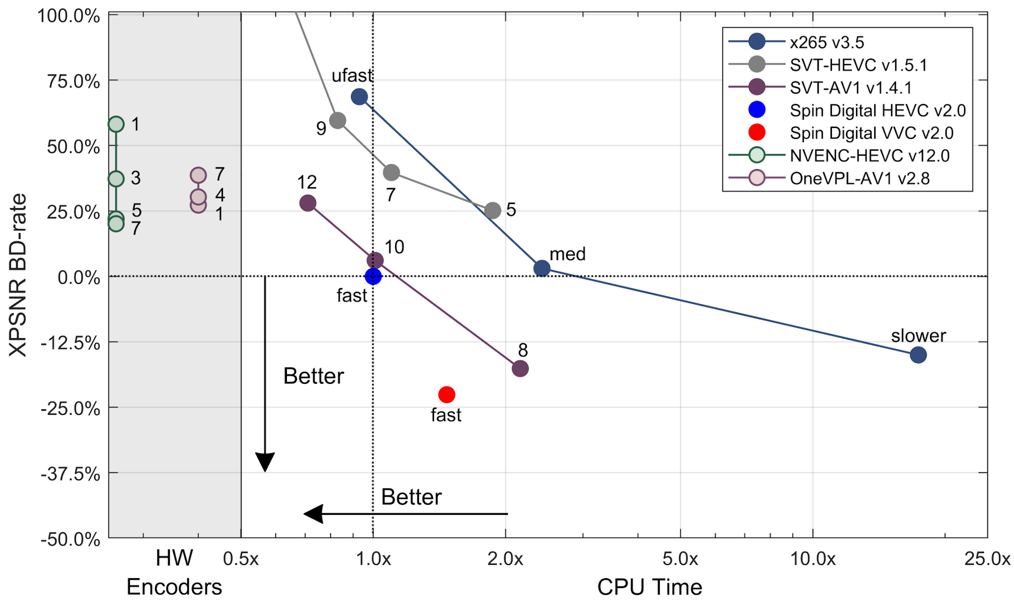

Figure 14: XPSNR BD-Rate and CPU utilisation time for 8K video relative to Spin Digital HEVC for the encoders and presets under evaluation

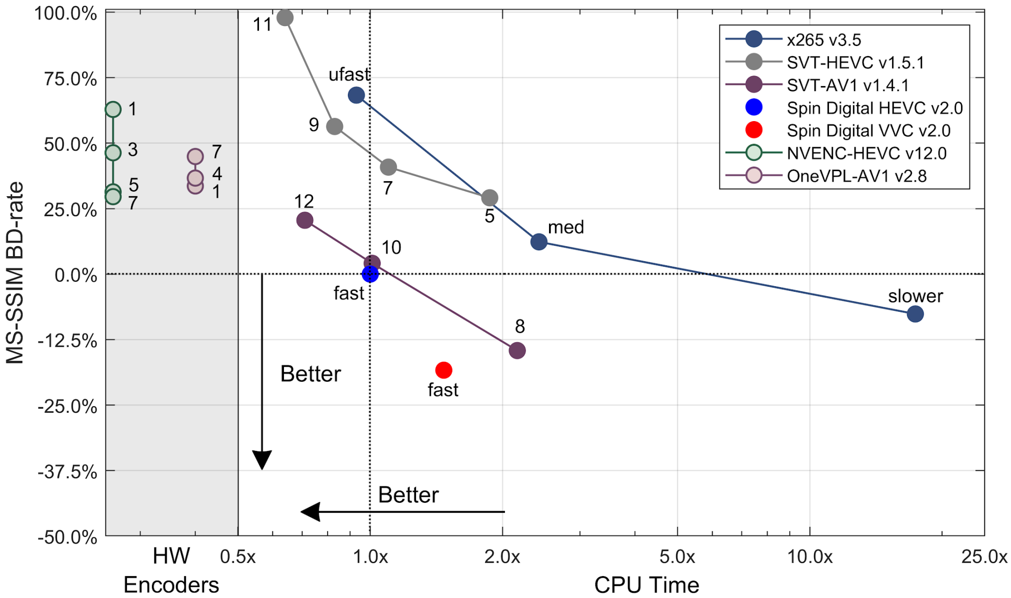

Figure 15: MS-SSIM BD-Rate and CPU utilisation time for 8K video relative to Spin Digital HEVC for the encoders and presets under evaluation

NVENC-HEVC and OneVPL-AV1 produce, respectively, PSNR BD-rate increases of up to 101% and 78% with respect to Spin Digital VVC.

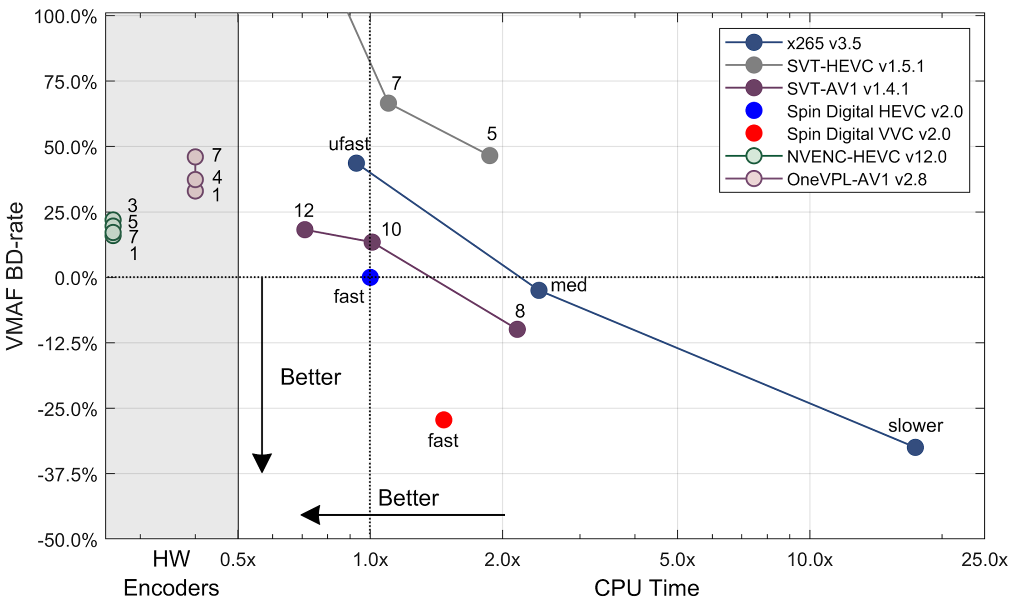

Figure 16: VMAF BD-Rate and CPU utilisation time for 8K video relative to Spin Digital HEVC for the encoders and presets under evaluation

In addition, Spin Digital VVC achieves a higher PSNR BD-rate savings (22.29%) than *SVT-AV1 - 8* (16.48%), where 8 is its highest quality preset for 8K video, while being 32% less complex (CPU time of 1.47x compared to 2.16x).

When compared to *x265 - slower*, Spin Digital VVC also provides similar or higher compression efficiency (e.g. -6.80% for PSNR, -11.37% for XPSNR, +4.05% for VMAF) () and, at the same time, about 12 times lower complexity (CPU time of 1.47x versus 17.38x).

It is also observed that both GPU-based hardware encoders exhibit high compression efficiency losses (PSNR BD-rate increases) with respect to Spin Digital HEVC and VVC. When compared to Spin Digital VVC, the BD-rate losses based on PSNR are: between 55% and 101% for NVENC-HEVC and between 63% and 78% for OneVPL-AV1.

6.3. COMPRESSION EFFICIENCY PER SEQUENCE

Table 8 shows detailed information per sequence on the BD-rate and CPU time achieved by Spin Digital VVC relative to the baseline.

Table 8: Results for 8K video in terms of BD-rate and CPU time for each 8K video sequence achieved by Spin Digital VVC referred to Spin Digital HEVC. The bitrate range for BD-rate calculation is from 30 Mbps to 100 Mbps

Video Sequence	PSNR BD-rate [%]	XPSNR BD-rate [%]	MS-SSIM BD-rate [%]	VMAF BD-rate [%]
BerlinSeqs	-21.88	-22.03	-18.66	-24.81
FollowCar	-27.41	-28.68	-25.25	-22.48
Fuji	-18.84	-19.73	-17.99	-26.32
Haru	-21.98	-21.76	-8.75	-35.48
Helicopter	-29.48	-28.79	-24.81	-37.34
MC2	-17.69	-19.36	-14.14	-19.29
Superposition	-21.40	-20.92	-19.90	-31.05
Teaser 1	-18.85	-18.79	-15.93	-18.55
Average	-22.29	-22.60	-18.34	-27.22

According to the results, Spin Digital VVC achieves consistent BD-rate gains across all test video sequences.

6.4. MULTITHREADED ENCODING SPEED

The software encoders were executed on the server with two Intel Xeon Platinum 8368 CPUs (2x 38 cores), which were configured enabling the maximum number of threads. The RTX 3070 and ARC A770 GPUs installed in the server were used to measure the performance of NVENC-HEVC and OneVPL-AV1, respectively.

BerlinSeqs (8Kp60 10-bit HDR) was the video clip used in these experiments, which is the most challenging sequence of the test set in terms of encoding speed and, at the same time, its BD-rate results are comparable to the average.

For each encoder and preset, the video was encoded at a bitrate that produced a PSNR of 44.4 dB, which is considered a broadcast-grade quality level for this sequence.

Figure 17 shows the encoding speed results for the bitrate required to obtain the same quality.

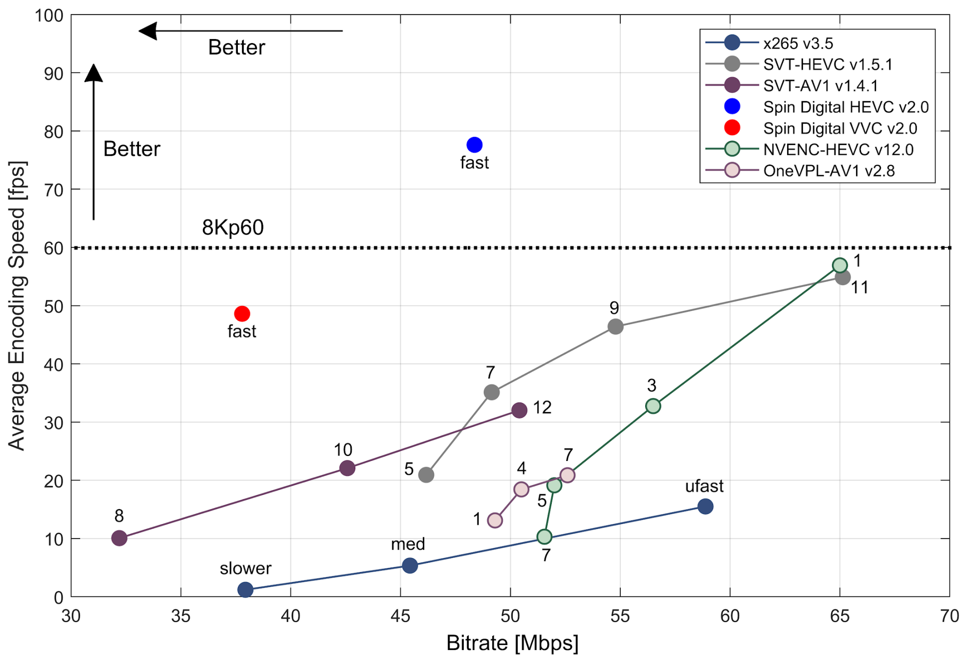

Figure 17: Actual bitrate for a PSNR of 44.4 dB and encoding speed produced by the encoders when encoding BerlinSeqs using two Intel Xeon Platinum 8368 CPUs (2x 38 cores) for the software encoders, the RTX 3070 GPU for NVENC, and the ARC A770 GPU for OneVPL

As can be observed, Spin Digital HEVC is able to produce a performance beyond 60 fps (77.61 fps) on a 2x38-core server, which is enough headroom to guarantee 8Kp60 real-time encoding.

The results also indicate that Spin Digital VVC has sufficient margin to compress 8Kp30 video in real-time (48.60 fps) on the same server.

At a similar encoding speed, this encoder produces a significantly lower bitrate than SVT-HEVC and NVENC-HEVC. For example, Spin Digital VVC generates a bitrate of 37.79 Mbps, whereas *SVT-HEVC - 9* and *NVENC-HEVC - 1* need to increase the bitrate by 58.2% and 72.0% to obtain the same quality.

The x265, SVT-AV1 and OneVPL encoders are not capable of producing the necessary performance to operate in real-time even at 30 fps. Although *SVT-AV1 - 12* produced an average speed of 32.2 fps, it has not enough headroom to guarantee stable real-time operation.

Spin Digital's VVC encoder is able to compress 8Kp30 video in real-time with the lowest bitrate for a given target quality using a dual-socket CPU server.

8K 60 fps live encoding is not possible with the current generation of CPU architectures. By combining Spin Digital software optimizations and the next generation of CPUs, which will include more and faster cores, the VVC encoder will be able to deliver broadcast grade-quality and reach the performance required for 8K live video encoding at 60 fps with 10-bit and HDR.

7. 4K/8K VVC LIVE STREAMING AND BROADCASTING

For a video encoder to work reliably in a live streaming environment, several requirements in terms of performance and features should be met:

- **High average encoding speed:** The performance of the encoder should be on average higher than the target video frame rate (e.g. 60 fps), with a sufficient tolerance margin so that the instantaneous speed does not fall below the target frame rate in case of complex scenes. This requirement has been proven in Sections 5.8 and 6.3 for the Spin Digital VVC encoder for 4Kp60 and 8Kp30 video, respectively.
- **Stable performance over time:** The encoder should also exhibit a stable encoding speed over time in order to prevent frame dropping that can degrade the temporal continuity of the encoded video.

- **Real-time operation mode:** The encoder should process the content at the target video resolution and frame rate, but if the content is too complex and the underlying compute architecture does not have the required performance, the encoder should drop input frames instead of adding encoding delay.

- **HRD compliance:** The synchronisation of encoders and decoders in live applications is defined by the HRD model, which specifies constraints on picture timing, buffer size and buffer handling. To ensure high-quality and smooth playback, appropriate encoding decisions should be made to prevent buffer overflows and underflows while providing consistent video quality over time.

- **I/O modules:** The live encoder should be equipped with I/O modules that can receive an uncompressed video and audio from the source (e.g. a camera) via SDI or a contribution stream over IP, and deliver the compressed output stream either over HTTP (e.g. HLS, DASH) or TS-over-IP (e.g. UDP, RTP, SRT), or both simultaneously.

As already stated in Section 4, the VVC encoder has been integrated into a complete framework (SDK) and application designed to fulfil all the above requirements (Figure 2).

Using the new encoder, a complete VVC live encoding, streaming, playback workflow for 4Kp60 and 8Kp30 10-bit video was demonstrated at the IBC Exhibition in Amsterdam on September 15-18, 2022 (Spin Digital 2 2022) as well as at InterBEE in Tokyo (Japan) on November 16-18, 2022 (Fraunhofer IIS 2022). Figure 18 shows live workflow in action at IBC 2022, which is composed of three components:

- **Uncompressed media player:** A real-time software media player developed by Spin Digital that plays uncompressed YUV video over 12G-SDI in 4K and 8K resolutions together with PCM audio (Spin Digital 3 2022).

- **VVC real-time encoder:** An encoding server with 12G-SDI video capture, VVC video and MPEG-H 3D audio encoding, and HTTP and TS-over-IP streaming modules (Spin Digital 2023).

- **VVC media player:** A playback PC running Spin Digital's VVC media player, which handles VVC and MPEG-H decoding, video and audio rendering, and 4K and 8K video output over GPU with HDMI interface (Spin Digital 4 2022).

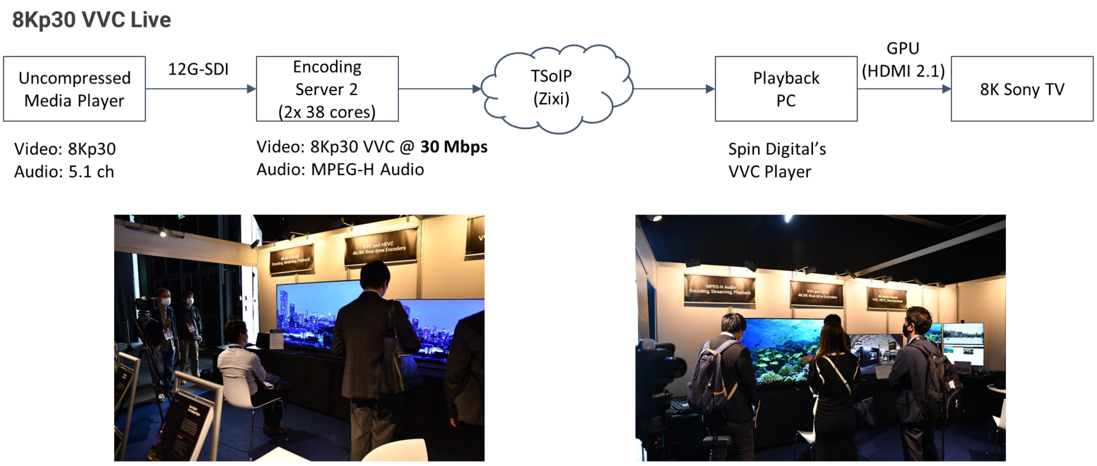

Figure 18: Spin Digital demonstrating live 8Kp30 VVC encoding, streaming, and playback at IBC 2022

This workflow demonstrates that VVC UHD live encoding and streaming is now possible with current computing technologies and highly optimised VVC encoder and decoder software solutions.

VVC UHD live encoding and streaming is now possible with Spin Digital's VVC encoder and decoder software solutions running on current computing technologies.

8. CONCLUSIONS

In this paper a VVC/H.266 real-time software encoder has been presented. The new encoder is designed to produce the compression, quality, and performance levels required for high-end UHD live streaming and broadcasting applications.

The main highlights of the VVC real-time encoder are summarised next:

- **Higher compression efficiency than a state-of-the-art HEVC live encoder:** The VVC encoder achieves, for 4K video, a BD-rate reduction of 17.5% with respect to a highly optimised HEVC real-time encoder (Spin Digital HEVC). This has been possible at the cost of 1.65 times the computational complexity of Spin Digital HEVC, which is considered reasonable and has been proven feasible with current generation of CPU architectures. The results for 8K video have shown that the VVC encoder developed by Spin Digital achieves a BD-rate savings of 25.9% relative to the HEVC live encoder with 1.45 times greater complexity.

- **Real-time UHD video encoding on a single dual-socket server:** The VVC encoder is a highly-optimised CPU-based software solution that can process 4K video at 60 fps as well as 8K video at 30 fps, both in 10-bit HDR, in real-time on a single server with two Intel Xeon Platinum CPUs with a total of 76 CPU cores.

- **Outperforming optimised software HEVC and AV1 encoders:** When running on a multi-core CPU system targeting 4K 60 fps real-time operation, the VVC encoder produces the required encoding performance and results in the highest compression efficiency when compared to optimised open-source HEVC and AV1 software encoders such as x265, SVT-HEVC, and SVT-AV1

- **Higher compression efficiency than hardware-accelerated encoders:** For 4K video, the NVENC-HEVC and OneVPL-AV1 encoders yield under real-time conditions, respectively, a BD-rate increase of about 20% relative to Spin Digital HEVC. These encoders produce BD-rate increases between 40% and 45% compared to Spin Digital's VVC encoder. The compression efficiency losses for 8K video are even higher: 55% (NVENC-HEVC) and 68% (OneVPL-AV1) when using their highest quality presets.

- **Ready for 4K/8K live streaming and broadcasting:** The VVC encoder has been integrated into a live encoding and streaming application and SDK developed by Spin Digital that includes: input capture via SDI and IP, pre-processing, pre-analysis, advanced rate control, audio and video encoding, and broadcast over IP and Internet streaming. Together with Spin Digital's VVC decoder and media player (Spin Player VVC), the end-to-end VVC encoding, streaming, and playback workflow has been successfully validated for 4Kp60 and 8Kp30 videos.

The VVC encoder assessed in this whitepaper is the first generation of a VVC CPU-based software implementation, and it is expected that the encoder will improve over time for delivering UHD live video at higher quality with lower bitrates. VVC live encoding improvements will emerge with the use of new and more advanced encoding algorithms combined with the increased performance of next-generation CPU architectures. As a result, it is expected that the VVC encoder will be able to compress 8Kp60 10-bit HDR video in real-time for live applications with increased compression and quality.

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