READY FOR DEPLOYMENT: VVC'S ADOPTION AND INTEROPERABILITY STATUS

Lukasz Litwic[1], Dmytro Rusanovskyy[2], Justin Ridge[3]

[1] Ericsson, Poland, [2] Qualcomm, USA, [3] Nokia, USA

ABSTRACT

As a core video coding standard, VVC (Versatile Video Coding) has been shown to achieve coding efficiency gains of 40-50% over previous-generation codecs. It has been surrounded by a suite of enabling specifications and has now been included in major broadcast application standards. This paper outlines the preparatory work that has been undertaken to enable VVC deployment; reviews the current deployment status of VVC (considering software and hardware, encoder and decoder); and describes the VVC Technical Guidelines distributed by the Media Coding Industry Forum (MC-IF), which are intended to assist with understanding VVC and incorporating it into a broadcast architecture.

INTRODUCTION

VVC coding technology has been developed and maintained by the Joint Video Experts Team (JVET), a joint video expert team of the Question 6 (VCEG) of ITU-T Study Group 16 and the MPEG group of ISO/IEC JTC 1/SC 29 since 2017. VVC version 1 (ITU-T Recommendation H.266 | International Standard 23090-3 (MPEG-I Part 3)), specifying core coding technology, was finalized in 2020 [1]. Version 2 of the standard, enabling support of higher of bit-depth and bitrates, was finalized in 2023. Associated metadata signalled in supplemental enhancement information (SEI) messages were specified in VVC standard itself and in the VSEI standard (Versatile SEI messages for coded video bitstreams) (ITU-T Recommendation H.274 | ISO/IEC 23002-7 [2]).

Following its finalization in 2020, VVC/H.266 has been investigated for inclusion in global and regional application specifications. These application specifications define VVC-based profiles and receiver capabilities. However, they usually do not prescribe or elaborate on how a corresponding service may be implemented, and do not specify the impact of codec's operational parameters on Quality of Service. Furthermore, VVC profiles and application specific constraints imposed on VVC across different specifications may vary due to different application requirements. To fill the gap for necessary information and facilitate better deployment of VVC, the Media Coding Industry Forum initiated development of VVC technical guidelines, with first version released in early 2024 [3]. The guidelines text was subject to a community review and attracted interest from vendors, SDOs and industry at-large.

This paper starts with an overview of the latest VVC adoption and deployment status including an overview and comparison of VVC profiles in major application standards. The paper provides an overview of the MC-IF VVC technical guidelines which document VVC interoperability points adopted across relevant application specifications. In addition, the guidelines extract the most relevant and novel elements from the VVC standard and provide direction on how to implement VVC in specific settings and configurations. The paper concludes with the discussion of anticipated operational bitrates with VVC.

VVC ADOPTION STATUS

Among the early references to the VVC coding technology are the group of systems and transport standards defined by ISO/IEC JTC 1/SC29 MPEG that are important for the rapid deployment of VVC:

- **MPEG-2 TS** (ISO/IEC 13818-1 **|** Rec. ITU-T H.222.0) - MPEG-2 Transport Stream is a container format used for encapsulation packetized elementary stream. VVC carriage in MPEG-2 Transport Stream was added in the 8th edition of ISO/IEC 13818-1 [4].
- **MPEG ISO Base Media File Format** (ISO/IEC 14496-15) - MPEG ISO Base Media File Format (ISO BMFF) standardized as ISO/IEC 14496-12, is a container for storage and carriage of timed media [5]. ISO/IEC 14496-15 standard (Amendment 2) (Carriage of network abstraction layer (NAL) unit structured video in the ISO base media file format) specifies how VVC is stored in file formats based on ISO BMFF [6]. Storage of both single-layer and multi-layer VVC bitstreams is defined. The standard also defines samples and sub-samples reflecting the high-level bitstream structure and independently decodable units such as rectangular regions comprising of VVC subpictures or slices, e.g., for immersive applications.
- **MPEG DASH** (ISO/IEC 23009-1) - MPEG-DASH is a media delivery protocol for Dynamic Adaptive Streaming over HTTP[7]. MPEG-DASH is codec agnostic and can be used with media codecs contained in MPEG ISO BMFF (ISO/IEC 14496-12) or MPEG-2 TS (ISO/IEC 13818-1). Integration of media codecs can be specified externally defined interoperability points, e.g., through DASH Industry Forum (DASH-IF). DASH-IF added VVC profile to its DASH-IF Interoperability Points guidelines in 2022 [8].
- **MPEG CMAF** (ISO/IEC 23000-19) - MPEG Common Media Application Format (CMAF) standardized in ISO/IEC 23000-19 [9] is a common streaming format driven by the convergence between MPEG-DASH and HTTP Live Streaming (HLS). VVC support was added in the 3rd edition of ISO/IEC 23000-19 in 2022. VVC is supported in MPEG CMAF through two media profiles. The baseline VVC media profile targets single layer bitstreams conforming to VVC Main 10 profile and Main Tier. The multilayer VVC media profile targets multilayer bitstreams conforming to VVC Multilayer Main 10 profile and Main Tier.
- **MPEG HEIF** (ISO/IEC 23008-12) - The High Efficiency Image File Format (HEIF) specified in ISO/IEC 23008-12 is a standard developed by MPEG for the storage of images and image sequences [10]. VVC support was added in the second edition of the standard in 2022.
- **MPEG OMAF** (ISO/IEC 23090-2) - The Omnidirectional Media Format (OMAF) is s a storage and streaming format for omnidirectional media, including 360˚ omnidirectional video specified in ISO/IEC 23090-2 [11]. The following VVC profiles have been added in the third edition of the standard: VVC-based simple tiling OMAF video profile, VVC-based viewport-independent OMAF video profile, OMAF VVC image profile, and CMAF media profile for the VVC-based viewport-independent OMAF video profile.

Another group of application specifications referring to VVC have been produced by TV broadcast and streaming oriented SDOs:

- The Advanced Television Systems Committee (ATSC) published A/345 VVC Video Candidate Standard in November 2023 [12]. The candidate standard describes video constraints for the use of VVC in the ATSC 3.0 Digital Television System. VVC profiles and constraints are aligned with MPEG CMAF.
- CTA Wave added VVC profile to its Web Application Video Ecosystem Content Specification (CTA-5001-D) in 2021 [13]. VVC profile and constraints are aligned with MPEG CMAF.
- The DVB project endorsed commercial requirements for next generation video codecs for advanced 4K and 8K services in July 2021 and added VVC to its core specification TS 101 154 in February 2022. An update to the DVB-DASH specification (TS 103 285) including VVC was published in [14]. ETSI's version of TS 101 154 including VVC was published in June 2023 [15].
- SCTE adopted VVC into its standards, SCTE 281-1 [16] and 281-2 [17] in March 2023. The standards specify the carriage of VVC for cable video services. VVC carriage based on MPEG-2 transport stream for linear delivery and based on SCTE 214-1 for adaptive bitrate streaming is specified.

VVC-related application requirements and constrains defined in the aforementioned specifications are summarized in Table 1. It is evident the SDOs have taken different approaches when defining VVC receiver capabilities. ATSC A/345 candidate standard defines three VVC profiles which are aligned in terms of pixel throughput (i.e., support of video formats up to 8Kp60) while differentiating functional capabilities such as scalable support between its profiles. On the other hand, DVB differentiated its profiles according to its definition of different UHD formats. It can also be observed that some SDOs have not defined on support of 8Kp120 video format, yet.

Application specification	**Media profile, conformance point**	**VVC profile**	**3840x2160 60 fps**	**3840x2160 120 fps**	**7680x4320 60 fps**	**7680x4320 120 fps**
ATSC A/345	Constrained baseline VVC	Main 10	✓	✓	✓	-
	Full range constrained baseline VVC	Main 10	✓	✓	✓	-
	Constrained Multilayer VVC	Main 10 Multilayer Main 10	✓	✓	✓	-
CTA-5001-D	CVVC	Main 10 Multilayer Main 10	✓	✓	✓	-
DVB TS 101 154	VVC HDR UHDTV-1	Main 10	✓	-	-	-
	VVC HFR UHDTV-1		✓	✓	-	-
	VVC HDR UHDTV-2		✓	✓	✓	-
	VVC HFR UHDTV-2		✓	✓	✓	✓
SCTE 281-1 2023	VVC	Main 10	✓	✓	✓	✓

Table 1 – Summary of VVC interoperability points in selected application specifications.

At the time of writing this paper, there has been ongoing work on defining VVC profiles in the following organizations:

- ARIB ISBD has been investigating VVC Main 10 and Multilayer Main 10 profiles for its next generation digital video broadcasting system. Technical requirements for the next-generation terrestrial broadcasting service, including high-level features of VVC video profiles, were published by Ministry of Internal Affairs and Communication in [18].
- Sistema Brasileiro de Televisão Digital (aka Forum SBTVD) has been working toward a new standard for Brazil known as TV 3.0 [19]. Forum SBTVD issued call for proposals (CfP) in July 2020. VVC was selected as the Video Base Layer Codec, for both 4K over OTA and 8K over OTT delivery. According to [19] work on TV3.0 specifications is expected to be finalized in 2024 and the launch is planned for 2025.

DEPLOYMENT STATUS OF VVC

Deployment of VVC services will depend on the wide availability of VVC decoders and encoders. Several software VVC decoder implementations have been released, including publicly available software [20][21], commercial decoder implementations and VVC video players for mobile and desktop platforms (e.g., [22][23]). In terms of decode capabilities, desktop players were reported to address 8Kp60 [24] and 8Kp120 formats [25]. For large scale deployments, hardware decode capabilities are typically required. In the TV and STB market segment, VVC decoders in SoCs were released in 2021 and 2022 with decode capabilities ranging from 4Kp60 [26][27] up to 8Kp120 [28]. [30] reported a commercial streaming service to TVs, with VVC playback enabled on more than 30 late-model TVs as of October 2023.

In terms of encoders, initial deployments comprised software encoders, both publicly available [29] and commercial implementations for offline encoding, several of which were reported to achieve the target 40-60% performance gains over x265, a widely-used open source HEVC implementation [30][31]. A recent study reported significant VVC compression gains over 60% benchmarked against a commercial real-time HEVC encoder [32] albeit the test VVC encoder operated at ~0.1x real-time speed running on the same compute platform. This result shows potential gains offered by VVC although these are not yet achievable in the first iteration of VVC real-time encoding products. At the same time several real-time capable VVC encoder implementations were reported: targeting 10-bit 4Kp60 [32] and up to 10-bit 8Kp60 [33] . A key economic factor in VVC deployment will be whether these performance gains can be achieved with a reasonable increase in compute.

Initial figures based on analysis of VVC and HEVC reference software models pointed to 10x increase on the encode side required to realize 50% gains. Data provided by commercial encoder vendors for their real-time VVC implementations indicate between 1.5x-2x increase in encoder complexity required to achieve around 20% compression performance gain over respective commercial HEVC implementations. It is acknowledged that this ‘early days’ performance is expected to improve dramatically over time as VVC implementations gain importance. More discussion on the expected operating bitrates with VVC is included in the following sections of this paper. Readers can find a comprehensive summary of VVC deployment status maintained by the chair of ISO/IEC JTC 1/SC 29 Gary Sullivan, with most recent publication available online [34].

MEDIA CODING INDUSTRY FORUM VVC TECHNICAL GUIDELINES

With an active adoption of VVC across several application specifications worldwide, MC-IF's Interoperability WG produced VVC technical guidelines [3] to provide broadcasters and streaming service providers with a reference point for understanding how VVC can be applied to their specific situations. Figure 1 shows scope of the guidelines based on a single video transmission step. In this figure, internal blocks correspond to technology-centric scope, external blocks correspond to application-centric scope.

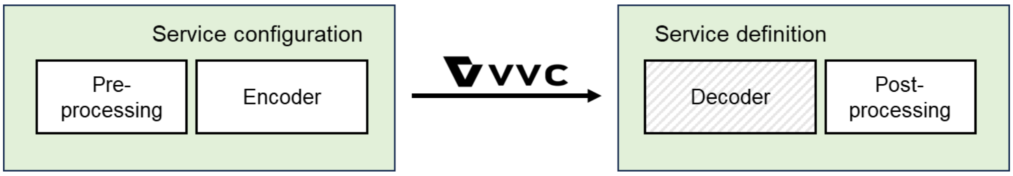

Figure 1 - Encoder-decoder video flow and scope of VVC technical guidelines.

The guidelines are organized in two parts. The first part provides a general overview of VVC standard and its usage and configuration aspects including, pre-processing, encoding and post-decoding processes. Encoding processes are not part of video coding standards. Therefore, encoder designs and algorithms can flexibly adapt to suit application needs. At the same time encoders have been shown in the past and are expected to improve their coding performance over time due to increasing computational resource availability and algorithmic innovation. The guidelines do not attempt to describe any particular encoder design or algorithms as would be implemented in real-life products. Instead, only relevant configuration aspects, agnostic of a particular encoder implementation or design, are covered. Examples of encoding processes include extended temporal prediction structures not possible in AVC or HEVC due to limits on storage of reference pictures or new features such as Reference Picture Resampling (RPR), which provides a baseline scalability feature that can be effectively used e.g., for a dynamic resolution coding in broadcast and streaming applications. Examples of post-processing processing include HDR metadata and film grain synthesis.

The second part provides information on VVC usage in broadcast and streaming applications from a service configuration point of view. The guidelines do not introduce any new interoperability points, but document VVC profiles defined by relevant SDOs and industry fora. One example is documentation of support for SDR and HDR video formats and associated metadata (see Table 2). HDR metadata referenced in the table include Mastering display colour volume (MDCV) SEI, Content light level information (CLLI) SEI, Content colour volume (CCV) SEI and Alternative transfer characteristics (ATC) SEI [2]. Dynamic HDR metadata carried as user registered metadata in Rec ITU-T T.35 SEI include SMPTE ST 2094-10 [26], SMPTE ST 2094-40 [36], SL-HDR1 (ETSI TS 103 433-1) [37] and SL-HDR2 (ETSI TS 103 433-2) [38].

<table>
<tr><th rowspan="3">Application specification</th><th colspan="17">System tag and metadata options</th></tr>
<tr><th colspan="3">SDR</th><th colspan="3">SDR-WCG</th><th>SDR-HLG</th><th>HDR-HLG</th><th colspan="6">HDR-PQ NCL</th><th>HDR-PQ ICtCp</th></tr>
<tr><th>-</th><th>MDVC</th><th>SL-HDR1</th><th>-</th><th>MDVC</th><th>SL-HDR1</th><th>ATC</th><th>-</th><th>-</th><th>MDVC</th><th>CLLI</th><th>ST 2094-10</th><th>SL-HDR2</th><th>ST-2094-40</th><th>-</th></tr>
<tr><td>ATSC A/345</td><td>✓</td><td colspan="2">(✓)</td><td>✓</td><td colspan="2">(✓)</td><td>-</td><td>✓</td><td>✓</td><td>✓</td><td colspan="4">(✓)</td><td>✓</td></tr>
<tr><td>CTA-5001-D</td><td>✓</td><td colspan="2">-</td><td>-</td><td colspan="2">-</td><td>-</td><td>-</td><td>✓</td><td>(✓)</td><td colspan="4">-</td><td>-</td></tr>
<tr><td>DVB TS 101 154</td><td>✓</td><td colspan="2">-</td><td></td><td colspan="2">-</td><td>✓</td><td>✓</td><td>✓</td><td colspan="5">(✓)</td><td>-</td></tr>
<tr><td>SCTE 281-1 2023</td><td colspan="3">✓</td><td colspan="3">-</td><td>-</td><td>-</td><td>✓</td><td>✓</td><td>(✓)</td><td>✓</td><td>-</td><td>✓</td><td>-</td></tr>
</table>

Table 2 – Support of HDR metadata and corresponding SEI messages. '✓' represents mandatory support, '(✓)' optional support and '-' no support.

Syntax parameter [VSEI/H.274]	**System tag**					
	SDR	**SDR-WCG**	**SDR-HLG**	**HDR-HLG**	**HDR-PQ NCL**	**HDR-PQ ICtCp**
vui_colour_primaries	1	9	9	9	9	9
vui_transfer_characteristics	1	14	14	18	16	16
vui_matrix_coeffs	1	9	9	9	9	14
vui_full_range_flag	0	0	0	0	0	1
vui_chroma_sample_loc_type_frame	0	2	2	2	2	2
preferred_transfer_characteristics	-	-	18	-	-	-

Table 3 Signalling for SDR and HDR video formats covered in Table 2.

The guidelines include discussion on configuration and signalling aspects for operational aspects such as random-access or zapping-time. The guidelines also cover signaling and configuration aspects for dynamic resolution change, new functionality enabled for VVC and not available for legacy profiles based on HEVC.

EXPECTED OPERATIONAL BITRATES WITH VVC

Compression performance is a key driver for adoption of new codecs. VVC provides substantial compression improvements over legacy codecs, allowing for better video quality at lower bitrates, resulting in cost savings and improved streaming performance. VVC performance has been corroborated by numerous studies and reports including objective and subjective performance tests which are summarized in clause 6.5 of VVC technical guidelines [3]. However, ultimately broadcasters and streaming operators are interested in operational bitrates which can be realized with new codecs and relevant bitrate and quality of service ranges used in these tests. Estimating operating bitrates can be quite complex as these ultimately depend on number of factors including video distribution formats (resolution and frame rates), content complexity, real-time vs. offline encoding and encoder's complexity and maturity. As described in earlier sections, offline VVC encoder were reported to achieve target performance gains of 40%-50% over HEVC. At the same time the first iteration of real-time encoder implementations was reported to realize lower compression performance gains of around 20% over HEVC. However, it can be expected though that subsequent iterations of encoder offerings will be able to full potential of the VVC standard when implementations mature and can benefit from advancements in computational performance as well as innovations in encoding algorithms.

The analysis of expected operational bitrates with VVC in the guidelines was aimed to provide implementation agnostic guidance on bitrate ranges which can be obtained with VVC. The first part of the analysis involved analysis of established operating bitrates used for emission with HEVC and estimating resulting VVC bitrates based on expected performance gains provided by VVC over HEVC. Table 4 provides a survey of reported HEVC bitrates used in broadcast and streaming.

Profile, tier, level	Spatial resolution	Max. frame rate	Bitrate(s) [Mbit/s]	Source
UHDTV 8K				
HEVC Main 10 MT L6.2	7840x4320	120	90-120	Rec. ITU-R BT.2073-2 [39]
HEVC Main 10 MT L6.1	7840x4320	60	80-100	Rec. ITU-R BT.2073-2 [39]
			28-113	Rec. ITU-R BT.2343-8 [40]
			25-80	3GPP TR: 26.925 [43]
UHDTV 4K				
HEVC Main 10 MT L5.2	3840x2160	120	35-50	Rec. ITU-R BT.2073-2 [39]
			30	Rec. ITU-R BT.2343-8 [40]
HEVC Main 10 MT L5.1	3840x2160	60	10-40	UHD Forum Guidelines [41]
			30-40	Rec. ITU-R BT.2073-2 [39]
			9-36	Rec. ITU-R BT.2343-8 [40]
			10.4-22.5	EBU TR 036 [44]
			8-16	3GPP TR: 26.925 [43]
			13.9 - 20	Apple HLS HEVC [42]
UHDTV 2K				
HEVC Main 10 MT L4.1	1920x1080	60	5-18	UHD Forum Guidelines [41]
			10-15	Rec. ITU-R BT.2073-2 [39]
			1.6-17	Rec. ITU-R BT.2343-8 [40]
			5-7	3GPP TR: 26.925 [43]
			5.4 – 9.7	Apple HLS HEVC [42]

Table 4 - Summary of HEVC recommended bitrates in final emission.

In particular, subjective assessment tests may be of great value to the industry when predicting bitrates at given picture quality ranges. MPEG conducted VVC verification in several application categories for which results are summarized in Figure 2.

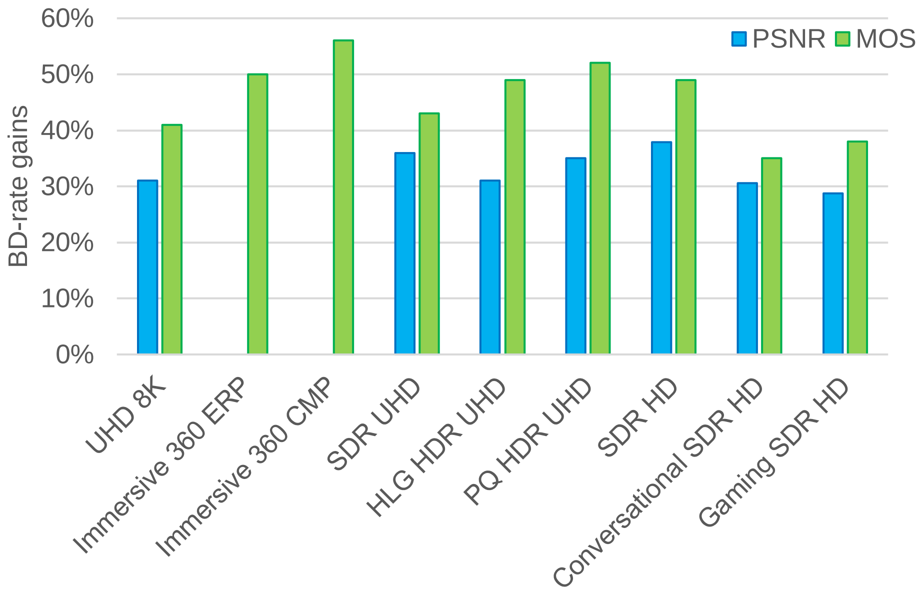

Figure 2 - Summary of reported VVC coding gains (objective – PSNR and subjective – MOS) over HEVC for various applications.

The results show that average bitrate savings provided by VVC over HEVC tend to be larger when assessed in subjective tests by viewers (bitrate savings measured for MOS in the range of 35%-55%) compared with objective measurements (bitrate savings measured for PSNR in the range of 30%-40%). For UHDTV 4K applications, reported operating bitrate range for HEVC are between 10-40 Mbit/s. This aligns with available guidance from streaming services requiring available bandwidth to be no less than 25 Mbit/s [45]. Assuming compression gains of between 40%-50% would result in a corresponding VVC operating bitrate range between 5-6 Mbit/s up to 20-24 Mbit/s.

Picture quality measurement and assessment methodologies such as ITU-R BT.500 typically involve evaluation of compression performance over extensive bitrate/quality range. This means that bitrate/quality points which are not suitable for operations due to very low quality are also included. The second part of analysis presented in the VVC technical guidelines investigates bitrate savings only in high quality range considered appropriate for broadcast and streaming applications. Based on available MPEG subjective test results, bitrates, and MOS scores for HEVC and VVC were interpolated for MOS=7 and MOS=8 which correspond to broadcast quality range. Figure 3 presents data for UHDTV 4K SDR and HDR test content.

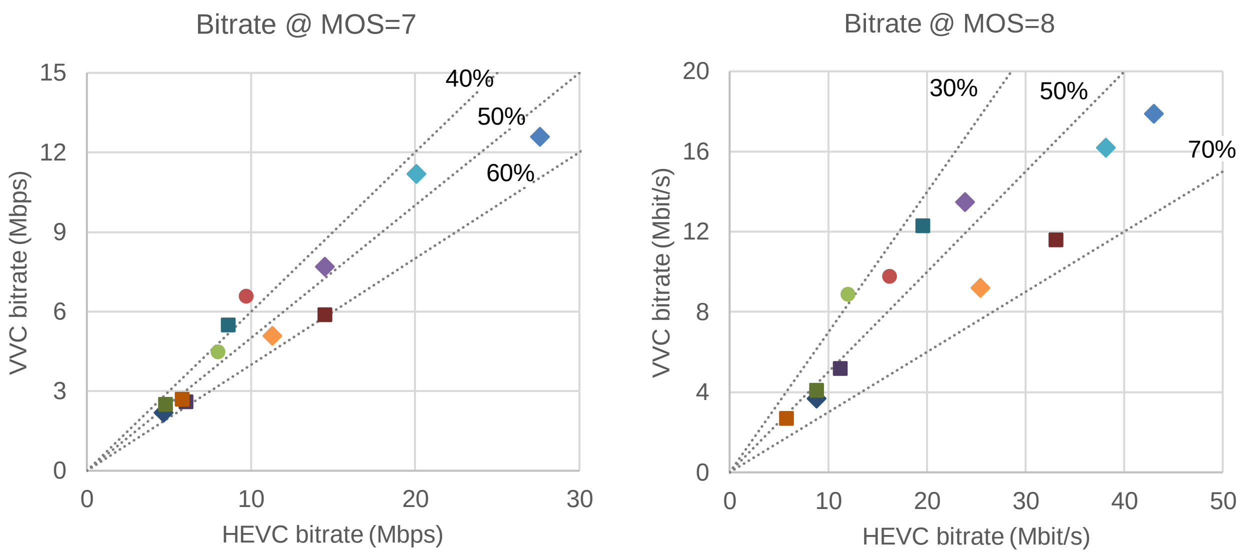

Figure 3 Scatter plots of HEVC and VVC bitrates for UHDTV 4K content at the same MOS quality (MOS=7 and MOS=8).
Dashed lines indicate achieved bitrate reduction for the same quality.
● - represents SDR sequence, ■ - represents HDR PQ SEQUENCE, ♦ - represents HDR HLG sequence.

The analysis of the provided MOS scores and corresponding bitrates shows that the expected compression efficiency gains were achieved at high quality range which is most relevant for broadcast and streaming services. It can be observed that for most test content VVC bitrates were between 3 – 13.5 Mbit/s and below 20 Mbit/s for few test sequences of higher complexity.

CONCLUSIONS AND FUTURE WORK

Much is required before a new video codec can be widely deployed. In the case of VVC, this paper has documented its inclusion in supporting specifications, and subsequently by global and regional broadcast and streaming bodies in application standards. Furthermore, VVC is now being implemented in both software and hardware and can be found in devices which are commercially available. Early results from commercial VVC encoders are documented, and in the future, these will become more compute-efficient and enable the full potential of compression efficiency gains offered by the VVC standard to be achieved.

This paper has also discussed the VVC Technical Guidelines, which are intended for those with a technical background who are considering integration of VVC into existing broadcast video environments. The Media Coding Industry Forum (MC-IF) intends to release an update to the guidelines incorporating additional aspects in the second half of 2024.

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