Performance Assessment of AV1, x265 and VVenC Open-Source Encoder Implementations Compared to VVC and HEVC Reference Software Models

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Agenda

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Motivation for this Study

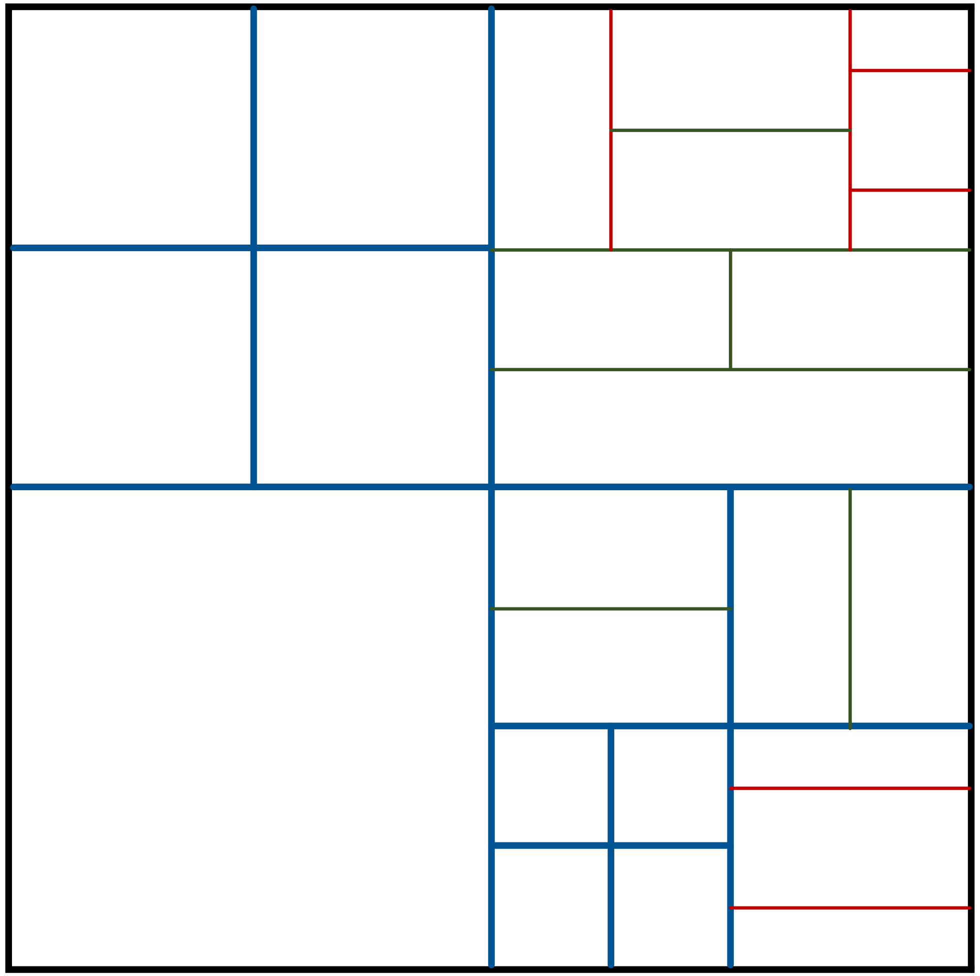
- **Currently, there are quite many different video codecs in the market and their comparative performance should be clarified;**
- The currently **most deployed** video codecs include:
  - **H.264/MPEG-AVC (2003):** is still most popular video coding standard being widely deployed for a variety of applications;
  - **H.265/MPEG-HEVC (2013):** is widely deployed in various applications;
  - **H.262/MPEG-2 (1995):** deployed mainly for broadcasting;
  - **H.266/MPEG-VVC (2020):** its worldwide deployment in various applications is constantly increasing;
  - **AV1 (2018):** developed by the Alliance of Open Media (AOM) as substitution to video coding standards.

VVC Standard Development

- **The exploration phase of the video technology beyond HEVC started in Oct. 2015;**
- Joint Video Experts Team (JVET) between ITU-T VCEG and ISO/IEC MPEG was established in Oct. 2017;
- Following the CfP responses, the development of the Versatile Video Codec (VVC) started in Apr. 2018;
- Just about 2 years later, **the 1st version of VVC was finalized in Jul. 2020;**
- In 2022, the VVC version 2 was approved, which refers to the integrated text additionally **containing operation range extensions, a new level (level 6.3), additional supplement enhancement information**, and corrections to various minor defects in the prior content of the specification.

VVC Main Technical Features

- ✓ Recursive quadtree (QT) with a nested recursive multi-type tree
- ✓ Reference picture resampling (adaptive spatial resolution)
- ✓ Subpictures concept (spatial random access)
- ✓ Separate chroma partitioning (chroma separate tree)
- ✓ Cross-component linear model (CCLM)
- ✓ Wide angular intra-prediction modes: 85 directional modes
- ✓ Matrix weighted prediction (MIP)
- ✓ Intra sub-partitions (ISP)
- ✓ Affine motion compensated prediction
- ✓ Geometric partitioning (GEO)
- ✓ Combined Inter and Intra prediction (CIIP)
- ✓ Bi-directional optical flow (BDOF)
- ✓ Multiple transform selection (MTS)
- ✓ Dependent quantization
- ✓ Adaptive loop filter (ALF)
- ✓ Intra block copy (IBC)
- ✓ Layered coding concept (scalability approach)



VVC QT with Binary and Ternary splits

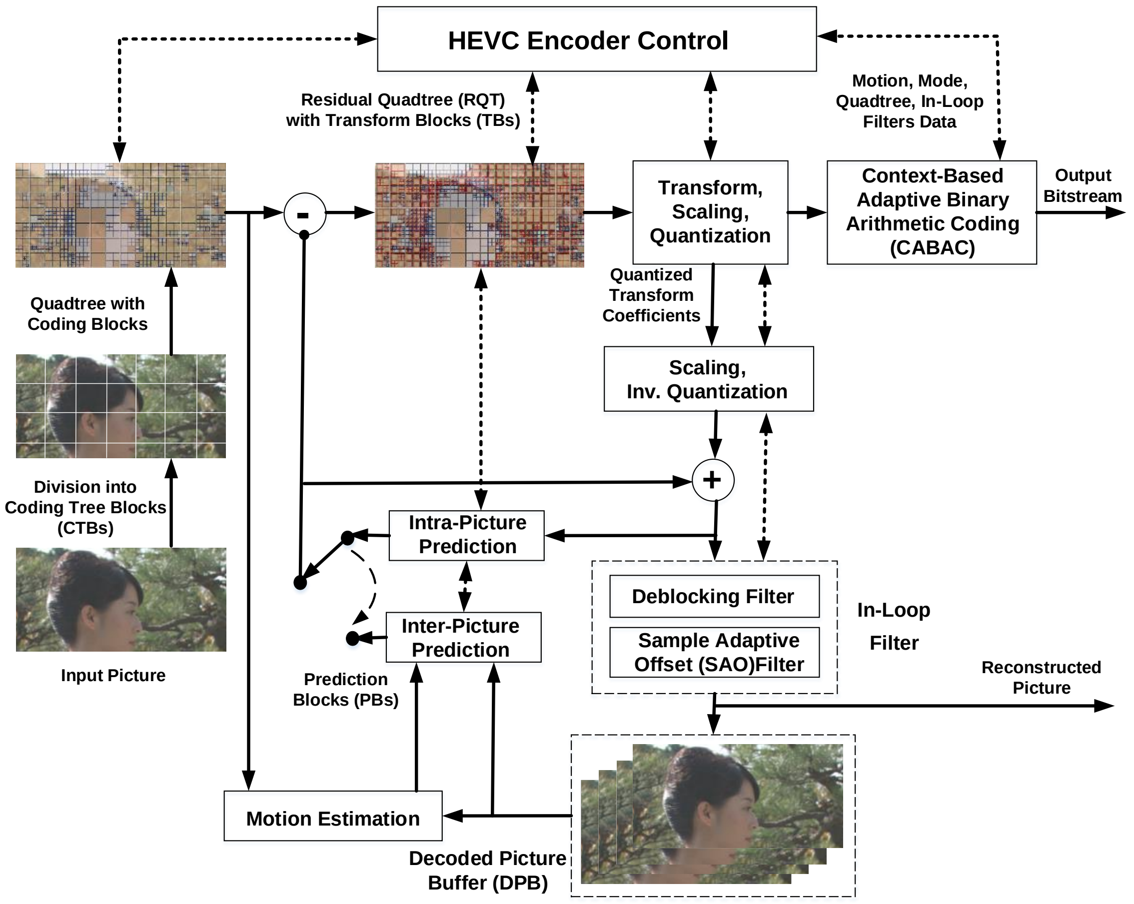
HEVC Standard Development

- ITU-T VCEG and ISO/IEC MPEG established **Joint Collaborative Team on Video Coding (JCT-VC)** and issued joint call for proposals (CfP) on video coding technology **in 2010**.

- As a result, there was an intensive development of the so-called **High-Efficiency Video Coding (HEVC)** standard during the next two and the half years.
  - **2013: HEVC version 1;**
  - **2014: HEVC version 2 -** Range Extensions (RExt), Scalable Extensions (SHVC), Multiview Extensions (MV-HEVC);
  - **2015: HEVC version 3 -** 3D Video Coding Extensions (3D-HEVC);
  - **2016: HEVC version 4 -** Screen Content Coding Extensions (HEVC-SCC);
  - **2018: HEVC version 5 -** additional SEI messages that include omnidirectional video SEI messages, a Monochrome 10 profile, a Main 10 Still Picture profile;
  - **2019: HEVC versions 6 and 7 -** additional SEI messages for SEI manifest and SEI prefix, additionally containing the fisheye video information SEI message and the annotated regions SEI message, along with some corrections to the existing specification text.
  - **2021: HEVC version 8 -** additional shutter interval information SEI message, along with corrections to the existing specification text.

HEVC Main Technical Features

- ✓ **Quadtree partitioning** for prediction and transform with large block sizes
- ✓ **Residual Quadtree (RQT)**
- ✓ Inter-picture prediction **block merging**
- ✓ **Advanced motion vector prediction** (AMVP)
- ✓ **¼-pel motion vector precision** using 8/7-tap luma and 4-tap chroma interpolation filters
- ✓ **Angular intra prediction (33 modes)**
- ✓ High-throughput transform coefficient coding
- ✓ **Sample adaptive offset** in-loop filtering (SAO)
- ✓ Transform skip mode for screen content coding
- ✓ **Parallel processing** with tiles and wavefronts
- ✓ Ultra-low delay processing with dependent slices

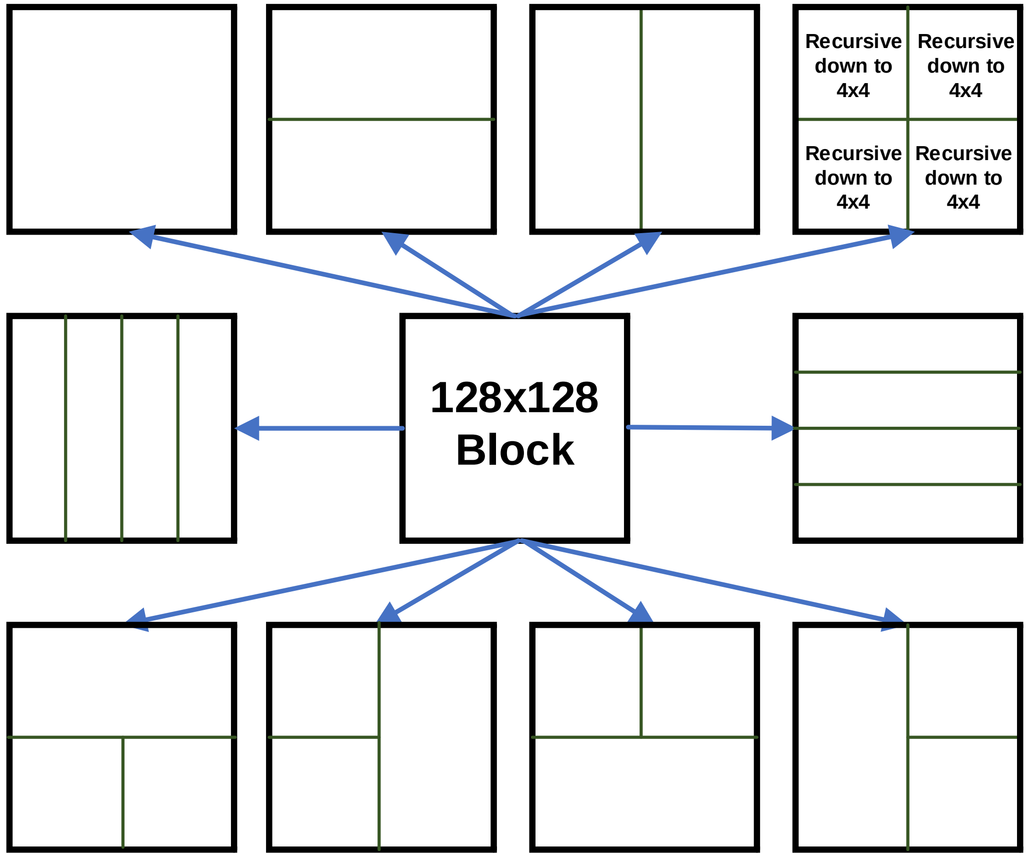


Alliance for Open Media (AOM)

- **AOM was formed in 2015, i.e. two years after the VP9 codec (developed by Google) was finalized.**
- The original founding members included Amazon®, Google®, Microsoft®, Cisco®, Intel®, Mozilla®, and Netflix®;
- **The work on AV1 started by using the source code of the above-mentioned VP9 codec**, further adding advanced tools on top of it;
- The Alliance for Open Media (AOM) released a baseline version of AV1 in April 2016;
- **AV1 version 1.0 was released in June 2018;**
- **AV1 version 2.0, was released in May 2020;**
- **AV1 version 3.0, was released in March 2021;**
- Up to date, 44 companies have joined AOM.

AV1 Main Technical Features

- Partition tree
- Enhanced directional intra prediction
- Recursive filtering-based intra predictor
- Chroma predicted from luma
- Color palette as a predictor
- Intra block copy
- Extended reference frames
- Dynamic spatial and temporal motion vector referencing
- Overlapped block motion compensation
- Warped motion compensation
- Advanced compound prediction
- Transform block partition
- Extended transform kernel
- Constrained directional enhancement filter
- Loop restoration filters
- Frame super-resolution
- Film grain synthesis
- Large-scale tiles
- Multi-symbol entropy coding
- Level map coefficient coding



AV1 codec's partitioning tree

Test Candidates

1. **VTM v17.0 of H.266/MPEG-VVC:** the VTM test model encoder of the VVC standard, developed by the Joint Video Experts Team (JVET);
2. **VVenC v1.7:** the VVenC open-source codec based on the VVC standard, developed by Fraunhofer HHI;
3. **HM v17.0 of H.265/MPEG-HEVC:** the HM test model encoder of the HEVC standard, developed by the Joint Collaborative Team on Video Coding (JCT-VC);
4. **x265 v3.5:** the x265 open-source encoder based on the HEVC standard, developed by Multicoreware;
5. **AV1 v3.6:** the libaom codec of the Alliance for Open Media (AOM).

Selected Encoder Configurations

- Random Access (RA) configuration, since it provides better results in term of coding efficiency compared to the Low Delay configuration;
- Intra Period was set to ~1 sec., according to the JVET Common Test Conditions (CTC);
- Group of Pictures (GOP) size was set to 16;
- The rate control for VTM and HM was disabled, since these encoders are single-pass encoders relying on framewise fixed/static QP settings and substantially do not incorporate a rate-control mechanism;
- Test conditions for VTM and HM have been aligned according to the JVET Common Test Conditions (CTC).
- AV1 was tested in a picture-level quantization mode with quality levels adjusted to fit the bitrates produced by the rest of tested encoders: 28, 39, 50, and 61.
- Two-pass rate control for AV1, VVenC and x265 was enabled, thereby leading to a coding gain increase in order to exploit their full potential.

AV1, x265 and VVenC Command Lines

AV1 Version	AOMedia Project AV1 Encoder 3.6.0-216-gb7440ea34 (Feb. 7, 2023)
Configuration with the Command Line Interface (CLI)	**--cpu-used=0** --tune=psnr --psnr --verbose --passes=2 --lag-in-frames=48 --frame-parallel=0 --threads=1 --tile-columns=0 --threads=1 **--end-usage=q** **--cq-level=*$CQ*** --min-gf-interval=16 --max-gf-interval=16 --enable-fwd-kf=1 --kf-min-dist=*$IntraPeriod* --kf-max-dist=*$IntraPeriod*

x265 Version	x265 encoder version 3.5+1-f0c1022b6
Configuration with the Command Line Interface (CLI)	**--preset placebo** --tune psnr --psnr **--crf=*$CRF*** --keyint=*$IntraPeriod* --min-keyint=*$IntraPeriod* --rc-lookahead=48 --no-scenecut --no-wpp --frame-threads=1 --qg-size=8 --subme 7 --pass=2

VVenC Version	Fraunhofer VVC Encoder ver. 1.7.0
Configuration with the Command Line Interface (CLI)	vvencFFapp -c randomaccess.cfg -c sequence.cfg

Experimental Results

4K and 1080p Test sequences from the JVET VVC Random Access CTC

Classes	Class A1 (10-bit)	Class A2 (10-bit)	Class B (10-bit/8-bit)
Resolution	*3840×2160 (4K)*	*3840×2160 (4K)*	*1920×1080 (FHD)*
Sequences	Tango2 (60fps)	CatRobot (60fps)	MarketPlace (60fps, 10-bit)
		DaylightRoad2 (60fps)	RitualDance (60fps,10-bit)
		ParkRunning3 (50fps)	Cactus (50fps, 8-bit)
			BasketballDrive (50fps, 8-bit)
			BQTerrace (60fps, 8-bit)

Experimental Results (Cont.)

BD-BR: Weighted $PSNR_{YUV}$

(negative BD-BR values indicate actual bit-rate savings)

Encoder	AV1	x265	VVenC	VTM	HM
AV1		-37.6%	31.2%	21.2%	-20.1%
x265	62.5%		118.0%	105.0%	30.0%
VVenC	-23.4%	-53.1%		-8.4%	-39.1%
VTM	-16.9%	-50.6%	9.6%		-34.1%
HM	25.5%	-22.1%	64.9%	52.4%	

Experimental Results (Cont.)

Summarized Computational Complexity (in term of encoding times) for the best performance encoders' configurations

Encoder	AV1	x265	VVenC	VTM	HM
AV1		x 4.6	x 1.9	x 0.4	x 4.6
x265	x 0.2		x 0.4	x 0.1	x 1.0
VVenC	x 0.5	x 2.5		x 0.2	x 2.5
VTM	x 2.7	x 12.4	x 5.0		x 12.4
HM	x 0.2	x 1.0	x 0.4	x 0.1	

Summary and Conclusions

- **VVenC vs. AV1: bit-rate savings of 23.4%** with only a half of the AV1 encoding run-time;
- **AV1 vs. HM: bit-rate savings of ~20%,** but with a factor of ~4.6 in the encoder run-time;
- **VVenC vs. VTM: bit-rate savings of 8.4%,** while VTM runs 5 times slower than VVenC;
- **HM vs. x265: bit-rate savings of ~22%,** with substantially the same encoding run-time (when x265 is running in the most slowest coding preset - *placebo*);
- **x265** has an **overhead of more than 100%,** when compared to VTM; however, VTM runs 12.4 times slower than x265 (in the *placebo* preset);
- **HM** has an **overhead of ~25%** when compared to AV1, and **about ~65%** when compared to VVenC.

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