Comparison Assessment of Emerging EVC and VVC Video Coding Standards with HEVC and AV1

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Agenda

I. Introduction
   • Motivation for this Study
   • Brief Intro into VVC, EVC, HEVC and AV1 Codecs

II. Main Technical Features of Selected Test Candidates

III. Detailed Experimental Results
   • AV1 in Quantization Mode (Fixed QP Structure)
   • AV1 in VBR Mode (Rate Control Enabled)

IV. Summary and Conclusions
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)**: its worldwide deployment in various applications is constantly increasing;
- **H.262/MPEG-2 (1995)**: deployed mainly for broadcasting;
- **AV1 (2018)**: developed by the Alliance of Open Media (AOM) as substitution to video coding standards;
- **VP9 (2013)**: being mainly supported in Internet applications.

Next Generation Video Coding Standards

- **H.266/MPEG-VVC**: Versatile Video Coding Standard is developed by a Joint Video Experts Team (JVET) between VCEG (Q6/16) and ISO/IEC JTC1 SC29/WG11 (MPEG), and its 1st version was finalized in 2020;
- **MPEG-5 Part 1**: Essential Video Coding (EVC) Standard is developed by MPEG, and its 1st version was finalized in 2020;
- **MPEG-5 Part 2**: Low Complexity Enhancement Video Coding (LCEVC) Standard is being developed by MPEG, and it is supposed to be finalized soon.
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;
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
EVC Main Technical Features

EVC Profiles

• Baseline profile: tools that were made public more than 20 years ago or for which only Type 1 declarations have been received in a previous standard
• Main profile: contains a small number of additional tools, each providing a significant gain
• Baseline Still Picture profile: contains tools that are used in Baseline profile to support a picture coding
• Main Still Picture profile: contains tools that are used in Main profile to support a picture coding

Structure of EVC profiles

• EVC baseline profile is a basis of EVC codec that is not overlapped with HEVC technology
• EVC Main profiles contains a small number of tools on top of baseline profile not using HEVC for the basis
• Most tools can be independently switched ON and OFF according to each user requirements
• When turning off a tool in Main profile, a baseline tool is used as a default tool for the same functionality
## EVC Main Technical Features (Cont.)

<table>
<thead>
<tr>
<th>Category</th>
<th>Tool in Baseline Profile</th>
<th>Tool in Main Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Partitioning</strong></td>
<td>• Tile &amp; Slice: no tile, no slice</td>
<td>• Tile &amp; Slice: support</td>
</tr>
<tr>
<td></td>
<td>• CTU size: 64</td>
<td>• CTU size: 128, 64, 32</td>
</tr>
<tr>
<td></td>
<td>• Block partitioning: QT</td>
<td>• Block Partitioning: BTT</td>
</tr>
<tr>
<td></td>
<td>• CTU size: 128, 64, 32</td>
<td>• Pipeline unit size: 64x64</td>
</tr>
<tr>
<td></td>
<td>• SUCO</td>
<td>• Local dual tree (for small chroma intra blocks)</td>
</tr>
<tr>
<td><strong>Intra</strong></td>
<td>• DC and 4 angular modes</td>
<td>• DC/Bi-linear/Plane and 30 angular modes</td>
</tr>
<tr>
<td></td>
<td>• Ref. sample filling: middle value of bit-depth</td>
<td>• Ref. sample filling: extrapolation from top-left ref. sample</td>
</tr>
<tr>
<td></td>
<td>• Mode coding: adaptive code word assignment</td>
<td>• Interpolation filter: 4-tap Gaussian filter</td>
</tr>
<tr>
<td></td>
<td>• Chroma mode: Direct mode only</td>
<td>• Mode coding: MPM + PIM5</td>
</tr>
<tr>
<td></td>
<td>• Constrained intra prediction</td>
<td>• Chroma mode: Direct mode + DC/Bi-linear/Hor./Ver.</td>
</tr>
<tr>
<td></td>
<td>• Skip mode: two indices signaling for both lists</td>
<td>• Intra block copy (IBC)</td>
</tr>
<tr>
<td></td>
<td>• Temporal direct mode</td>
<td>• Constrained intra prediction</td>
</tr>
<tr>
<td></td>
<td>• 6-tap MC interpolation (wiener filter)</td>
<td></td>
</tr>
<tr>
<td><strong>Transform</strong></td>
<td>• DCT2 (64x64 - 2x2)</td>
<td>• DCT2 (64x64 – 2x2) w/ internal bit-depth consideration</td>
</tr>
<tr>
<td><strong>Quantization</strong></td>
<td>• CU-level delta QP: CU based</td>
<td>• ATS (Intra: a.k.a. MTS, Inter: a.k.a. SBT)</td>
</tr>
<tr>
<td></td>
<td>• Chroma QP mapping table (from H.264)</td>
<td>• CU-level delta QP: region based</td>
</tr>
<tr>
<td></td>
<td>• Chroma QP mapping table (from HEVC)</td>
<td>• Chroma OP mapping table (from HEVC)</td>
</tr>
<tr>
<td></td>
<td>• Chroma OP mapping table signaling in SPS</td>
<td>• Chroma OP mapping table signaling in SPS</td>
</tr>
<tr>
<td><strong>In-loop filtering</strong></td>
<td>• DBF: H.263 + adaptive boundary strength</td>
<td>• DBF: HEVC w/ minor modification</td>
</tr>
<tr>
<td></td>
<td>• CABAC w/o context modeling &amp; initialization</td>
<td>• ALF, HTDF (post-reconstruction filtering)</td>
</tr>
<tr>
<td></td>
<td>• Coefficient coding: Run/Level/Last coding</td>
<td>• Tile boundary filtering on/off</td>
</tr>
<tr>
<td></td>
<td>• CABAC</td>
<td>• DRA for HDR</td>
</tr>
<tr>
<td><strong>Entropy coding</strong></td>
<td>• POC: no signaling</td>
<td>• CABAC</td>
</tr>
<tr>
<td></td>
<td>• Picture size: multiple of 8</td>
<td>• Coefficient coding: Advanced coefficient coding</td>
</tr>
<tr>
<td></td>
<td>• Reference picture management: using GOP information</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• NAL: 2-byte header, IDR/Non-IDR/SPS/PPS/APS/SEI/FD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Tool set indicator</td>
<td></td>
</tr>
<tr>
<td><strong>High level syntax</strong></td>
<td>• POC: LSB signaling</td>
<td>• POC: no signaling</td>
</tr>
<tr>
<td></td>
<td>• Picture size: multiple of 8</td>
<td>• Picture size: multiple of 8</td>
</tr>
<tr>
<td></td>
<td>• Reference picture management: Reference picture list (RPL)</td>
<td>• Reference picture management: using GOP information</td>
</tr>
<tr>
<td></td>
<td>• NAL: 2-byte header, IDR/Non-IDR/SPS/PPS/APS/SEI/FD</td>
<td>• NAL: 2-byte header, IDR/Non-IDR/SPS/PPS/APS/SEI/FD</td>
</tr>
<tr>
<td></td>
<td>• Tool set indicator</td>
<td>• Tool set indicator</td>
</tr>
</tbody>
</table>
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 a 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.
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;
- In turn, the AV1 version 1.0 was released in 2018;
- Currently, at least 44 companies have joined AOM;
- Recently, AV1 codec had a major update since 2018, and its 2nd version, i.e. AV1 version 2.0, was released in May 2020.
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 9.0 of H.266/MPEG-VVC**: the VTM test model encoder of the VVC standard, developed by the Joint Video Experts Team (JVET);

2. **ETM 6.0 of MPEG-5 EVC**: the ETM test model encoder of the EVC standard, developed by the Moving Picture Experts Group (MPEG);

3. **HM 16.18 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. **AV1 2.0.0**: a video-coding scheme 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.;

- **The rate control for VTM, ETM 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, ETM and HM have been aligned according to the Common Test Conditions (CTC).

- AV1 in the Quantization mode:
  - **Fixed QP range**, further defining slightly different minimal and maximal QPs to allow AV1 to use different QPs for key frames (KFs) and for non-KFs, for example, thereby **allowing a fairer comparison of the AV1 coding structure with the VTM, ETM and HM hierarchical structure**;

- AV1 in the VBR mode:
  - AV1 is known not to perform so well with the Fixed QP (range) settings due to a lack of an efficient hierarchical structure. Therefore, in the VBR mode, AV1 encoder is allowed to significantly vary QP to achieve a larger coding gain;
  - **Two-pass rate control for AV1 was enabled**, thereby leading to a coding gain increase in order to exploit AV1’s full potential.
## Test Methodology and Evaluation Setup

### VTM reference software configuration according to CTC

<table>
<thead>
<tr>
<th>Coding options</th>
<th>Chosen parameters</th>
<th>Coding options (cont.)</th>
<th>Chosen parameters (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder Version</td>
<td>VTM 9.0</td>
<td>Intra Period</td>
<td>1 sec</td>
</tr>
<tr>
<td>Profile</td>
<td>Main 10 4:2:0</td>
<td>CTU Size</td>
<td>128</td>
</tr>
<tr>
<td>Rate Control</td>
<td>Disabled</td>
<td>Maximum CU Width/Height</td>
<td>64</td>
</tr>
<tr>
<td>R/D Optimization</td>
<td>Enabled</td>
<td>Internal Bit Depth</td>
<td>8/10</td>
</tr>
<tr>
<td>GOP</td>
<td>16</td>
<td>GOP-Based Temporal Filter</td>
<td>Disabled</td>
</tr>
<tr>
<td>Motion Estimation</td>
<td>TZ search</td>
<td>DeltaQpRD</td>
<td>Disabled</td>
</tr>
<tr>
<td>MinSearchWindow</td>
<td>96</td>
<td>Deblocking Filter</td>
<td>Enabled</td>
</tr>
<tr>
<td>Search Range</td>
<td>384</td>
<td>Adaptive Loop Filter</td>
<td>Enabled</td>
</tr>
<tr>
<td>Adaptive Motion Search Range</td>
<td>Enabled</td>
<td>Sample Adaptive Offset (SAO)</td>
<td>Enabled</td>
</tr>
<tr>
<td>MinSearchWindow</td>
<td>96</td>
<td>Intra Block Copy (IBC)</td>
<td>Disabled</td>
</tr>
<tr>
<td>Hierarchical Encoding</td>
<td>Enabled</td>
<td>Geometric Partitioning Mode (GEO)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Multiple transform selection (MTS)</td>
<td>Enabled</td>
<td>Bi-directional Optical Flow (BIO)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Subblock transform (SBT)</td>
<td>Enabled</td>
<td>Bi-prediction with CU-level Weight (BCW)</td>
<td>Enabled</td>
</tr>
<tr>
<td>TransformSkip</td>
<td>Enabled</td>
<td>Combined Inter/Intra Prediction (CIIP)</td>
<td>Enabled</td>
</tr>
<tr>
<td>TransformSkipFast</td>
<td>Enabled</td>
<td>Affine</td>
<td>Enabled</td>
</tr>
<tr>
<td>Hadamard ME</td>
<td>Enabled</td>
<td>Intra sub-partitions (ISP)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Fast Encoder</td>
<td>Enabled</td>
<td>Matrix weighted Intra Prediction (MiP)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Fast Merge Decision</td>
<td>Enabled</td>
<td>Merge mode with MVD (MMVD)</td>
<td>Enabled</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Symmetric MVD (SMVD)</td>
<td>Enabled</td>
</tr>
</tbody>
</table>
### ETM reference software configuration according to CTC

<table>
<thead>
<tr>
<th>Coding options</th>
<th>Chosen parameters</th>
<th>Coding options (cont.)</th>
<th>Chosen parameters (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder Version</td>
<td>ETM 6.0</td>
<td>Intra Period</td>
<td>1 sec</td>
</tr>
<tr>
<td>Rate Control</td>
<td>Disabled</td>
<td>Maximum CU Width/Height</td>
<td>64</td>
</tr>
<tr>
<td>GOP</td>
<td>16</td>
<td>Internal Bit Depth</td>
<td>8/10</td>
</tr>
<tr>
<td>R/D Optimization</td>
<td>Enabled</td>
<td>Deblocking Filter</td>
<td>Enabled</td>
</tr>
<tr>
<td>Binary Ternary Tree (BTT)</td>
<td>Enabled</td>
<td>Adaptive Loop Filter</td>
<td>Enabled</td>
</tr>
<tr>
<td>Split Unit Coding Order (SU CO)</td>
<td>Enabled</td>
<td>Advanced Deblocking Filter (ADDB)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Hierarchical Encoding</td>
<td>Enabled</td>
<td>Hadamard Transform Domain Filter (HTDF)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Adaptive Motion Vector Resolution (AMVR)</td>
<td>Enabled</td>
<td>Intra Block Copy (IBC)</td>
<td>Disabled</td>
</tr>
<tr>
<td>Merge mode with MVD (MMVD)</td>
<td>Enabled</td>
<td>Enhanced Intra Prediction Directions (EIPD)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Affine</td>
<td>Enabled</td>
<td>Improved Quantization and Transform (IQT)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Decoder-side Motion Vector Refinement (DMVR)</td>
<td>Enabled</td>
<td>Adaptive Transform Selection (ATS)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Advanced Motion Vector Prediction (ADMVP)</td>
<td>Enabled</td>
<td>Advanced Coefficient Coding (ADCC)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Reference Picture Lists (RPL)</td>
<td>Enabled</td>
<td>Picture Order Count Signalling (POCS)</td>
<td>Enabled</td>
</tr>
</tbody>
</table>
**Test Methodology and Evaluation Setup (Cont.)**

<table>
<thead>
<tr>
<th>Coding options</th>
<th>Chosen parameters</th>
<th>Coding options (cont.)</th>
<th>Chosen parameters (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder Version</td>
<td>HM 16.18</td>
<td>Intra Period</td>
<td>1 sec</td>
</tr>
<tr>
<td>Profile</td>
<td>Main 10</td>
<td>Coding Unit Size/Depth</td>
<td>64/4</td>
</tr>
<tr>
<td>Rate Control</td>
<td>Disabled</td>
<td>Transform Unit Size (Min/Max)</td>
<td>4/32</td>
</tr>
<tr>
<td>R/D Optimization</td>
<td>Enabled</td>
<td>Internal Bit Depth</td>
<td>8/10</td>
</tr>
<tr>
<td>GOP</td>
<td>16</td>
<td>Deblocking Filter</td>
<td>Enabled</td>
</tr>
<tr>
<td>Search Range</td>
<td>64</td>
<td>Fast Encoding</td>
<td>Enabled</td>
</tr>
<tr>
<td>Motion Estimation</td>
<td>TZ search</td>
<td>Fast Merge Decision</td>
<td>Enabled</td>
</tr>
<tr>
<td>TransformSkip</td>
<td>Enabled</td>
<td>Sample adaptive offset (SAO)</td>
<td>Enabled</td>
</tr>
<tr>
<td>TransformSkipFast</td>
<td>Enabled</td>
<td>Asymmetric Motion Partitioning (AMP)</td>
<td>Enabled</td>
</tr>
<tr>
<td>Hadamard ME</td>
<td>Enabled</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fixed QP Structure Configuration

<table>
<thead>
<tr>
<th>AV1 Version</th>
<th>AV1 v2.0.0: aomedia/aom/refs/tags/v2.0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Git aom/tag</td>
<td>d1d1226af626a61f7ca664b270dd473b92228984 (May 18, 2020)</td>
</tr>
<tr>
<td>Configuration with the Command Line Interface (CLI)</td>
<td>--cpu-used=0 --tune=psnr --frame-parallel=0 --tile-columns=0 --threads=1 --end-usage=q --min-q=[QP] --max-q=[QP+8] --min-gf-interval=16 --max-gf-interval=16 --kf-min-dist=[INTRA-PERIOD] --kf-max-dist=[INTRA-PERIOD] --bit-depth=[BIT-DEPTH]</td>
</tr>
</tbody>
</table>

- **Fixed QP range**, further defining slightly different minimal and maximal QPs to allow the usage of different QPs (e.g., for key frames (KFs) and for non-KFs), thereby allowing a fairer comparison of the AV1 coding structure with the VTM, ETM and HM hierarchical structure;

- The *IntraPeriod* intervals were set to be similar to those used for running VTM, ETM, and HM;

- The rest of settings are aligned with VTM, ETM, and HM.
### Two-Pass Rate-Control AV1 Configuration

<table>
<thead>
<tr>
<th>AV1 Version</th>
<th>AV1 v2.0.0: aomedia/aom/refs/tags/v2.0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Git aom/tag</td>
<td>d1d1226af626a61f7ca664b270dd473b92228984 <em>(May 18, 2020)</em></td>
</tr>
<tr>
<td>Configuration with the Command Line Interface (CLI)</td>
<td>--cpu-used=0 --tune=psnr --passes=2 --frame-parallel=0 --tile-columns=0 --threads=1 --end-usage=vbr --min-q=0 --max-q=63 --min-gf-interval=16 --max-gf-interval=16 --kf-min-dist=[INTRA-PERIOD] --kf-max-dist=[INTRA-PERIOD] bit-depth=[BIT-DEPTH] --target-bitrate=[BIT RATE OF VTM/ETM/HM]</td>
</tr>
</tbody>
</table>

- AV1 can significantly vary QP - from 0 to 63 in order to achieve larger coding gains;
- The *IntraPeriod* intervals were set to be similar to those used for running VTM, ETM, and HM;
- Similarly, the target bitrate was set to match the bitrate of VTM, ETM, and HM;
- The rest of settings are aligned with VTM, ETM, and HM.
Experimental Results

Test sequences according to the JVET VVC random access CTC:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>3840×2160 (4K)</td>
<td>3840×2160 (4K)</td>
<td>1920×1080 (FHD)</td>
<td>832×480</td>
<td>416×240</td>
<td>Varying Resolution</td>
</tr>
<tr>
<td>Sequences</td>
<td>Tango2 (60fps)</td>
<td>CatRobot (60fps)</td>
<td>MarketPlace (60fps, 10-bit)</td>
<td>RaceHorses (30fps)</td>
<td>RaceHorses (30fps)</td>
<td>ArenaOfValor (60fps, 1920×1080)</td>
</tr>
<tr>
<td></td>
<td>FoodMarket4 (60fps)</td>
<td>DaylightRoad2 (60fps)</td>
<td>RitualDance (60fps, 10-bit)</td>
<td>BQMall (60fps)</td>
<td>BQSquare (60fps)</td>
<td>BasketballDrillText (50fps, 832×480)</td>
</tr>
<tr>
<td></td>
<td>Campfire (30fps)</td>
<td>ParkRunning3 (50fps)</td>
<td>Cactus (50fps, 8-bit)</td>
<td>PartyScene (50fps)</td>
<td>BlowingBubbles (50fps)</td>
<td>SlideEditing (30fps, 1280×720)</td>
</tr>
<tr>
<td></td>
<td>BasketballDrive (50fps, 8-bit)</td>
<td>BasketballDrill (50fps)</td>
<td>BasketballPass (50fps)</td>
<td>SlideShow (20fps, 1280×720)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BQTerrace (60fps, 8-bit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental Results

Experimental results summary of bit-rate savings in terms of BD-BR PSNR\textsubscript{YUV} of VVC, EVC and AV1 encoders vs. HEVC encoder per JVET CTC:

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

<table>
<thead>
<tr>
<th>Classes of Sequences</th>
<th>HM 16.18 is an Anchor</th>
<th>VVC vs. HEVC</th>
<th>EVC vs. HEVC</th>
<th>AV1 (with the fixed QP structure) vs. HEVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A1</td>
<td></td>
<td>-39.57%</td>
<td>-27.26%</td>
<td>-1.61%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td>(excl. &quot;Campfire&quot;)</td>
<td>(excl. &quot;Campfire&quot;)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.26x</td>
<td>2.91x</td>
<td>3.50x</td>
</tr>
<tr>
<td>Class A2</td>
<td></td>
<td>-42.86%</td>
<td>-30.51%</td>
<td>-0.02%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td>(excl. &quot;DaylightRoad2&quot;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.33x</td>
<td>4.51x</td>
<td>5.94x</td>
</tr>
<tr>
<td>Class B</td>
<td></td>
<td>-37.18%</td>
<td>-23.28%</td>
<td>15.61%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td></td>
<td>5.20x</td>
<td>7.05x</td>
</tr>
<tr>
<td>Class C</td>
<td></td>
<td>-30.32%</td>
<td>-17.49%</td>
<td>24.42%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td></td>
<td>6.29x</td>
<td>6.43x</td>
</tr>
<tr>
<td>Class D</td>
<td></td>
<td>-27.46%</td>
<td>-15.83%</td>
<td>28.24%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td></td>
<td>6.67x</td>
<td>8.09x</td>
</tr>
<tr>
<td>Class F</td>
<td></td>
<td>-42.41%</td>
<td></td>
<td>14.38%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td></td>
<td>6.66x</td>
<td>3.39x</td>
</tr>
<tr>
<td>Average BD-BR</td>
<td></td>
<td>-36.11%</td>
<td>-21.98%</td>
<td>16.33%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td></td>
<td></td>
<td>10.49x</td>
<td>5.25x</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.99x</td>
</tr>
</tbody>
</table>
**Experimental Results (Cont.)**

BD-BR: Weighted PSNR$_{YUV}$ for 4K/2160p
AV1 with the fixed QP structure
(negative BD-BR values indicate actual bit-rate savings)

<table>
<thead>
<tr>
<th>CODECS</th>
<th>VVC</th>
<th>EVC</th>
<th>HEVC</th>
<th>AV1</th>
</tr>
</thead>
<tbody>
<tr>
<td>VVC</td>
<td></td>
<td>-17.5%</td>
<td>-41.2%</td>
<td>-39.3%</td>
</tr>
<tr>
<td>EVC</td>
<td>21.3%</td>
<td></td>
<td>-28.9%</td>
<td>-26.3%</td>
</tr>
<tr>
<td>HEVC</td>
<td>70.2%</td>
<td>44.4%</td>
<td></td>
<td>1.3%</td>
</tr>
<tr>
<td>AV1</td>
<td>66.3%</td>
<td>36.9%</td>
<td>-0.8%</td>
<td></td>
</tr>
</tbody>
</table>
Experimental Results (Cont.)

Experimental results summary of bit-rate savings in terms of BD-BR PSNR YUV of VVC, EVC and AV1 encoders vs. HEVC encoder per JVET CTC:

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

<table>
<thead>
<tr>
<th>Classes of Sequences</th>
<th>HM 16.18 is an Anchor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VVC vs. HEVC</td>
<td>EVC vs. HEVC</td>
</tr>
<tr>
<td><strong>Class A1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>-39.57%</td>
<td>-27.26%</td>
</tr>
<tr>
<td></td>
<td>8.26x</td>
<td>2.91x</td>
</tr>
<tr>
<td><strong>Class A2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>-42.86%</td>
<td>-30.51%</td>
</tr>
<tr>
<td></td>
<td>9.33x</td>
<td>4.51x</td>
</tr>
<tr>
<td><strong>Class B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>-37.18%</td>
<td>-23.28%</td>
</tr>
<tr>
<td></td>
<td>10.00x</td>
<td>5.20x</td>
</tr>
<tr>
<td><strong>Class C</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>-30.32%</td>
<td>-17.49%</td>
</tr>
<tr>
<td></td>
<td>11.75x</td>
<td>6.29x</td>
</tr>
<tr>
<td><strong>Class D</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>-27.46%</td>
<td>-15.83%</td>
</tr>
<tr>
<td></td>
<td>13.00x</td>
<td>6.67x</td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>-42.41%</td>
<td>-16.34%</td>
</tr>
<tr>
<td></td>
<td>6.66x</td>
<td></td>
</tr>
<tr>
<td><strong>Average BD-BR</strong></td>
<td>-36.11%</td>
<td>-21.98%</td>
</tr>
<tr>
<td>Factor of the HM Encoder Run Time</td>
<td>10.49x</td>
<td>5.25x</td>
</tr>
</tbody>
</table>

Dec. 1, 2020

Mile High Video 2020
Experimental Results with VBR AV1 Configuration (Cont.)

BD-BR: Weighted PSNR\textsubscript{YUV} for 4K/2160p
AV1 with in the VBR Mode (with the rate control enabled)
(negative BD-BR values indicate actual bit-rate savings)

<table>
<thead>
<tr>
<th>CODECS</th>
<th>VVC</th>
<th>EVC</th>
<th>HEVC</th>
<th>AV1</th>
</tr>
</thead>
<tbody>
<tr>
<td>VVC</td>
<td></td>
<td>-17.5%</td>
<td>-41.2%</td>
<td>-24.2%</td>
</tr>
<tr>
<td>EVC</td>
<td>21.3%</td>
<td></td>
<td>-28.9%</td>
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</tr>
<tr>
<td>HEVC</td>
<td>70.2%</td>
<td>44.4%</td>
<td></td>
<td>25.4%</td>
</tr>
<tr>
<td>AV1</td>
<td>32.1%</td>
<td>9.9%</td>
<td>-20.0%</td>
<td></td>
</tr>
</tbody>
</table>
Summary and Conclusions

- **VVC vs. HEVC:** bit-rate savings of around 40% for encoding 4K/2160p video sequences with a factor of ~9 in the encoder run-time;

- **EVC vs. HEVC:** bit-rate savings of around 30% for encoding 4K/2160p video sequences, while encoding approximately twice faster than VTM;

- **AV1 (fixed QP structure) vs. HEVC:** bit-rate savings of around ~1% only for encoding 4K/2160p video sequences, with a factor of ~4.7 in the encoder run-time;

- **VVC vs. AV1 (fixed QP structure):** bit-rate savings of around 39% for encoding 4K/2160p video sequences with a factor of ~2 in the encoder run-time;

- **EVC vs. AV1 (fixed QP structure):** bit-rate savings of around 26% for encoding 4K/2160p video sequences, while encoding approximately 1.3 times faster than AV1;

- **AV1 (2-pass rate control) vs. HEVC:** bit-rate savings of around 20% for encoding 4K/2160p video sequences, with a factor of ~3.4 in the encoder run-time.
Literature

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Dec. 1, 2020

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