**Abstract**—HEVC HM 16 includes a Coding Unit (CU) level perceptual quantization technique named AdaptiveQP. AdaptiveQP adjusts the Quantization Parameter (QP) at the CU level based on the spatial activity of samples in the four constituent N×N sub-blocks of the luma Coding Block (CB), which is contained within a 2N×2N CU. In this paper, we propose C-BAQ, which, in contrast to AdaptiveQP, adjusts the CU level QP according to the spatial activity of samples in the four constituent N×N sub-blocks of both the luma and chroma CBs. By computing the sum of luma, chromaCb and chromaCr spatial activity in a CU, a richer reflection of spatial activity in the CU is attained. Therefore, a more appropriate CU level QP can be selected, thus leading to important improvements in terms of coding efficiency. We evaluate the proposed technique in HEVC HM 16.7 using 4:2:2 and 4:2:0 YCbCr sequences. Both subjective and objective evaluations are undertaken during which we compare C-BAQ with AdaptiveQP. The objective evaluation reveals that C-BAQ attains a maximum BD-Rate reduction of 15.9% (Y), 13.1% (Cr) and 16.1% (Cb) in addition to a maximum decoding time reduction of 11%.0.

1. INTRODUCTION

In the context of video coding, numerous psychophysical experiments reveal that the Human Visual System (HVS) is less sensitive to quantization distortions within regions of video data that comprise significant sample variations in the spatial domain [1, 2]. Consequently, higher levels of quantization can be applied to these high activity regions, thus achieving bitrate savings without incurring a discernable loss of perceptual reconstruction quality. HEVC HM 16 includes a CU level adaptive quantization technique named AdaptiveQP, which is adopted from MPEG-2 Test Model 5 [3, 4]. AdaptiveQP exploits the aforementioned decreased ability of the HVS to perceive quantization distortions in regions consisting of high spatial variations of luma samples. This is achieved by applying a higher QP (a larger quantization step size), at the CU level, to high luma spatial activity regions. Conversely, a lower CU level QP is applied to low luma spatial activity regions since artifacts in areas of this nature are typically conspicuous [3]. The AdaptiveQP method achieves its objective by modifying the QP of a 2N×2N CU according to the spatial variance of samples in the four constituent N×N sub-blocks of the luma CB [3].

To the best of our knowledge, color-based CU level quantization has not been previously explored in HEVC research. However, methods similar to AdaptiveQP have been previously proposed. The method in [5] exploits the intensity masking phenomenon of the HVS and applies it to HEVC. This technique is modeled on the Just Noticeable Distortion (JND) approach and, therefore, perceptually adjusts quantization based on the intensity of luma samples. The proposed technique in [6] is a transform coefficient level technique that quantizes coefficients individually in a Transform Block. In contrast to Uniform Reconstruction Quantization, this method reduces the quantization step size for low frequency transform coefficients.

2. PROPOSED METHOD

We propose a CU level color-based adaptive quantization contribution named C-BAQ. C-BAQ improves upon AdaptiveQP by taking into account the spatial activity of the chroma data, in addition to the luma data, in a 2N×2N CU. That is, in contrast to AdaptiveQP, the proposed C-BAQ method acknowledges the samples in the constituent N×N sub-blocks of the Y CB, the Cr CB and Cb CB, thereby potentially deriving a more appropriate QP for a 2N×2N CU. The reason a more appropriate QP can be selected is as follows: each CB within a CU contains important spatial information. Therefore, it is desirable to account for the samples in both luma and chroma CBs because doing so results in a more wholesome reflection of the spatial activity in the 2N×2N CUs within a picture. In other words, the refined CU level QP more accurately reflects the spatial data contained within the CU. Consequently, important coding efficiency improvements are attained by C-BAQ. Note that chromaCb and chromaCr color components are integral aspects of YCbCr video data. For instance, if the chroma samples are aggressively subsampled, this typically results in the palpable reduction of visual quality in the video sequence. Recent developments in ITU-T HEVC version 3 with RExt [10] and Ultra HD technologies, which conform to ITU-R Recommendation BT.2020 chroma sampling (Rec. BT.2020 includes YCbCr 4:4:4 and 4:2:2 [11]), provide evidence that chroma data plays a major role as regards visual quality.

Before explaining C-BAQ in detail, it is appropriate to distinguish the 2N×2N CU, the N×N CU and the CB. Assuming that the split flag is enabled, the 2N×2N CU comprises four constituent N×N CUs (see Fig. 1). The Largest Coding Unit (LCU) supports 64×64 samples and the Smallest Coding Unit (SCU) supports 8×8 samples. LCUs operate at QuadTree (QT) Depth Level=0 and SCUs operate at QT Depth Level=3 [7, 8, 9]. The proposed C-BAQ method and AdaptiveQP do not operate below QT Depth Level=2. The CU, at all QT depth levels, comprises three CBs (assuming that the input video data is not monochrome): one Y CB, one Cb CB and one Cr CB.

The rest of this paper is organized as follows. Section 2 includes technical information on AdaptiveQP. Section 3 includes technical information on the proposed C-BAQ technique. Section 4 includes the evaluations, results and discussion of the proposed method. Finally, Section 5 concludes this paper.
Fig. 2. Sizes of CB sub-blocks in a 2N×2N CU: Y (gray), Cb (blue), Cr (red). In C-BAQ, there are four constituent sub-blocks of the Y, Cb and Cr CBs in a 2N×2N CU. Each subfigure specifies the size of CB sub-blocks for different input video data: (a) for 4:4:4 YCbCr video data, the sub-block sizes for Y, Cb and Cr are all N/2×N/2; (b) for YCbCr 4:2:2 video data, the sub-block sizes are as follows: Y = N/2×N/2, Cb = (N/2)×N and Cr = (N/2)×(N/2); (c) for YCbCr 4:2:0 video data, the sub-block sizes are as follows: Y = N/2×N, Cb = (N/2)×(N/2) and Cr = (N/2)×(N/2).

2. ADAPTIVE QP TOOL IN HEVC

As previously stated in Section 1, AdaptiveQP is a CU level perceptual quantization technique that modifies the QP of a 2N×2N CU based on the spatial variance of samples in the four constituent N×N sub-blocks of the luma CB. Therefore, a higher QP value can be applied to high luma spatial activity regions in a picture. Conversely, a lower QP value can be utilized in low luma spatial activity regions. The CU level QP, denoted as Q, is computed in (1) [3]:

\[ Q = q + \left[ 6 \times \log_2 \left( \frac{N}{2} \right) \right] \]  

(1)

where \( q \) corresponds to the slice level QP and \( n \) refers to the normalized spatial activity of luma samples in a CU. Variable \( n \) is computed in (2):

\[ n = \frac{m \times \left( f \times (l) \right) + t}{l + f \times t} \]  

(2)

where \( f \) is a scaling factor associated with the QP adaptation range \( a \); \( a \) is the maximum offset value permitted for the QP value in the CU, where the default value is \( a = 6 \). Variable \( l \) corresponds to the spatial activity of luma samples in the CU and \( t \) refers to the average activity for all CUs in a picture; \( f \) and \( l \) are computed in (3) and (4), respectively:

\[ f = 2^a \]  

(3)

\[ l = 1 + \min \left( y^2_k \right) \]  

(4)

where \( y^2_k \) corresponds to the variance of samples in an N×N luma CB sub-block, where the sub-block is denoted as \( k \). Variable \( y^2_k \) is quantified as the variance of luma pixel values, which is computed in (5):

\[ y^2_k = \frac{1}{z} \sum_{i=1}^{z} (w_i - u)^2 \]  

(5)

where \( z \) corresponds to the number of samples in an N×N luma CB sub-block (see Fig. 2). Variable \( w_i \) refers to the \( i \)th sample in the luma CB and \( u \) denotes the mean pixel value of the luma CB sub-block, which is computed in (6):

\[ u = \frac{1}{z} \sum_{i=1}^{z} w_i \]  

(6)

3. PROPOSED C-BAQ TECHNIQUE

As previously described in Section 1, the proposed C-BAQ technique improves upon AdaptiveQP by accounting for the spatial activity of chroma samples, in addition to luma samples, in a 2N×2N CU. C-BAQ modifies the 2N×2N CU level QP based on the spatial variance of samples in the four constituent N×N sub-blocks of all three CBs (the Y CB, the Cb CB and the Cr CB). The primary objective as regards acknowledging the Cb and Cr data, in addition to the Y data, is to derive a more appropriate QP selection for the 2N×2N CU to improve coding efficiency. The CU level QP, denoted as \( \tilde{Q} \), is computed in (7):

\[ \tilde{Q} = q + \left[ 6 \times \log_2 \left( \frac{N}{2} \right) \right] \]  

(7)

where \( \bar{n} \) denotes the normalized sum of luma and chroma sample spatial activity in a CU. Variable \( \bar{n} \) is computed in (8):

\[ \bar{n} = \frac{(f \times (l + b + d)) + t}{l + b + d + f \times t} \]  

(8)

where variables \( b \) and \( d \) correspond to the spatial activity of chroma Cb and chroma Cr samples in a CU, respectively. Variables \( b \) and \( d \) are computed in (9) and (10), respectively:

\[ b = 1 + \min \left( g^2_k \right) \]  

(9)

\[ d = 1 + \min \left( h^2_k \right) \]  

(10)

where \( g^2_k \) and \( h^2_k \) refer to the variance of samples in the Cb CB and Cr CB sub-blocks, where the sub-blocks are denoted as \( k \). Variables \( g^2_k \) and \( h^2_k \) are computed as the variance of Cr and Cb pixel values, respectively, as shown in (11) and (12):

\[ g^2_k = \frac{1}{m} \sum_{i=1}^{m} (v_i - o)^2 \]  

(11)

\[ h^2_k = \frac{1}{m} \sum_{i=1}^{m} (j_i - x)^2 \]  

(12)

where \( m \) refers to the number of samples in the Cb CB and the Cr CB sub-blocks (see Fig. 2). Variables \( v_i \) and \( j_i \) correspond to the \( i \)th samples in the Cb CB and the Cr CB, respectively. Variables \( o \) and \( x \) denote the mean pixel values of the Cb CB and the Cr CB sub-blocks, respectively, which are quantified in (13) and (14):

\[ o = \frac{1}{m} \sum_{i=1}^{m} v_i \]  

(13)

\[ x = \frac{1}{m} \sum_{i=1}^{m} j_i \]  

(14)
4. EXPERIMENTAL EVALUATIONS & DISCUSSION

We evaluate C-BAQ and compare it with AdaptiveQP (reference anchor). We integrate C-BAQ into HEVC HM 16.7 RExt [12] and undertake simulation tests that correspond, as closely as possible, to JCT-VC’s Common Test Conditions and Software Reference Configurations [13]. C-BAQ is a HVS-based perceptual quantization technique; therefore, it is appropriate to undertake subjective quality in addition to objective quality evaluations. Note that the subjective evaluation is vital because it allows us to fairly assess the perceptual reconstruction quality of the video data coded with C-BAQ and AdaptiveQP. The full experimental setup is as follows (the JCT-VC test sequences used in the evaluations are shown in Table 1):

- **Metric:** Subjective Evaluations & BD-Rate [14].
- **QPs:** 22, 27, 32 and 37.
- **Encoding Configurations:** All Intra & Random Access.
- **Encoding Profiles:** Main, Main_422_10, Main_444_10, Main_444, Main_422_10_Intra, Main_444_10_Intra and Main_444_Intra [13].

### Table 1. BD-Rate results attained by the proposed C-BAQ technique compared with AdaptiveQP. The All Intra results are shown on the left and the Random Access results are shown on the right. Negative percentages indicate performance improvements of the proposed C-BAQ method.

| Sequence          | C-BAQ versus AdaptiveQP (YCbCr 4:2:0) – All Intra | C-BAQ versus AdaptiveQP (YCbCr 4:2:0) – Random Access |
|-------------------|-----------------------------------------------|-----------------------------------------------|
|                    | BD-Rate %          | Runtimes %          | BD-Rate %          | Runtimes %          |
| FourPeople (8-bit) | −9.5 −8.6 −9.9 −3.7 −6.1 | FourPeople (8-bit) | −8.7 −7.5 −8.0 −0.3 −0.9 |
| KristenAndSara (8-bit) | −14.3 −12.3 −12.5 −4.9 −9.7 | KristenAndSara (8-bit) | −15.5 −12.8 −11.8 −0.9 −2.5 |
| ParkScene (8-bit)  | −5.4 −8.0 −7.8 −1.8 −2.2 | ParkScene (8-bit) | −4.0 −6.1 −6.2 −0.1 −1.3 |
| Traffic (8-bit)    | −8.6 −10.6 −13.5 −2.4 −6.1 | Traffic (8-bit) | −4.9 −7.0 −9.0 −0.4 −1.3 |

| Sequence          | C-BAQ versus AdaptiveQP (YCbCr 4:2:2) – All Intra | C-BAQ versus AdaptiveQP (YCbCr 4:2:2) – Random Access |
|-------------------|-----------------------------------------------|-----------------------------------------------|
|                    | BD-Rate %          | Runtimes %          | BD-Rate %          | Runtimes %          |
| PeopleOnStreet (8-bit) | −9.8 −13.4 −9.6 −0.2 −5.5 | PeopleOnStreet (8-bit) | −5.3 −5.5 −3.9 0.0 0.0 |
| DuckAndLegs (10-bit) | −6.0 −4.2 −8.3 −1.2 −2.9 | DuckAndLegs (10-bit) | −8.0 −9.2 −11.0 −0.3 −1.1 |
| ParkScene (10-bit)  | −9.7 −9.2 −16.1 −3.2 −11.0 | ParkScene (10-bit) | −7.5 −12.8 −13.5 0.0 −3.4 |
| Traffic (10-bit)    | −9.2 −12.2 −15.3 −2.9 −6.7 | Traffic (10-bit) | −5.0 −9.3 −11.4 0.1 0.1 |

| Sequence          | C-BAQ versus AdaptiveQP (YCbCr 4:4:4) – All Intra | C-BAQ versus AdaptiveQP (YCbCr 4:4:4) – Random Access |
|-------------------|-----------------------------------------------|-----------------------------------------------|
|                    | BD-Rate %          | Runtimes %          | BD-Rate %          | Runtimes %          |
| PeopleOnStreet (8-bit) | −11.8 −14.0 −9.0 −6.0 −3.4 | PeopleOnStreet (8-bit) | −6.7 −7.1 −6.4 −0.6 1.8 |
| DuckAndLegs (10-bit) | −14.0 −7.0 −11.2 −2.1 −5.1 | DuckAndLegs (10-bit) | −15.9 −13.1 −16.1 −0.2 0.3 |
| ParkScene (10-bit)  | −15.6 −8.7 −19.3 −3.9 −6.6 | ParkScene (10-bit) | −12.0 −16.4 −17.0 0.0 −1.8 |
| Traffic (10-bit)    | −11.1 −13.4 −15.9 −2.6 −5.9 | Traffic (10-bit) | −5.6 −11.3 −11.9 −0.1 1.1 |

4.1 Subjective Evaluation & Coding Efficiency Results

Five researchers in video processing performed a subjective evaluation, during which they analyzed the visual differences of the reconstructed sequences in a side-by-side comparison— one coded using C-BAQ and the other coded using AdaptiveQP. In this informal evaluation, no differences were reported in the vast majority of cases (see Fig. 3 and Fig. 4 for some comparisons). As shown in Table 1, for both the All Intra and Random Access simulations, significant coding efficiency improvements are attained by the proposed C-BAQ method in comparison with AdaptiveQP. For the All Intra simulations, considerable coding efficiency improvements are accomplished, which are as follows. For the 4:2:0 simulations, BD-Rate reductions of −14.3% (Y), −12.3% (Cb) and −12.5% (Cr) are achieved on the 4:2:0 8-bit KristenAndSara sequence (Main encoding profile). For the 4:2:2 simulations, BD-Rate reductions of −9.2% (Y), −12.2% (Cb) and −15.3% (Cr) are attained on the 4:2:2 10-bit Traffic sequence (Main_422_Intra encoding profile). For the 4:4:4 simulations, noteworthy BD-Rate reductions of −15.6% (Y), −8.7% (Cb) and −19.3% (Cr) are accomplished on the 4:4:4 10-bit ParkScene sequence (Main_444_Intra encoding profile).
AdaptiveQP Tool - Chroma Cb
ParkScene sequence tests.

Improvement is achieved for the 4:4:4 PeopleOnStreet sequence, with a reduction of $-11.0\%$.

In the All Intra tests, the most significant encoding time improvement is achieved for the 4:4:4 PeopleOnStreet sequence, with a reduction of $-0.9\%$.

In the Random Access tests, the differences in encoding times are marginal. Moreover, moderate decoding time reductions are achieved. The highest encoding time attained is for the 4:2:0 KristenAndSara sequence, with a reduction of $-0.9\%$. A moderate decoding time is attained for the 4:2:2 ParkScene sequence, with a reduction of $-3.4\%$.

4.3 Discussion

In the evaluation, the encoding time and decoding time performances of C-BAQ, in the majority of cases, proved to be consistently superior in comparison with AdaptiveQP.

With respect to C-BAQ’s coding efficiency improvements in the All Intra simulations, Fig. 5 and Fig. 6 show plots for the luma component and chroma components, respectively, on the 4:4:4 10-bit ParkScene sequence tests.

Similar to the All Intra simulation results, significant coding efficiency improvements are accomplished for the Random Access simulations, which are as follows. BD-Rate reductions of $-15.9\%$ (Y), $-13.1\%$ (Cb) and $-16.1\%$ (Cr) are attained on the 4:4:4 10-bit DuckAndLegs sequence (Main_444_10 encoding profile). For the 4:4:4 simulations, considerable BD-Rate reductions of $-15.9\%$ (Y), $-13.1\%$ (Cb) and $-16.1\%$ (Cr) are attained on the 4:4:4 10-bit DuckAndLegs sequence (Main_444_10 encoding profile).

In relation to C-BAQ’s coding efficiency improvements in the Random Access simulations, Fig. 7 and Fig. 8 show plots for the luma component and chroma components, respectively, on 4:4:4 10-bit DuckAndLegs sequence tests.

4.2 Encoding & Decoding Time Results

In the evaluation, the encoding time and decoding time performances of C-BAQ, in the majority of cases, proved to be consistently superior in comparison with AdaptiveQP.

In the All Intra tests, the most significant encoding time improvement is achieved for the 4:4:4 PeopleOnStreet sequence, with a reduction of $-6.0\%$. The most noteworthy decoding time reduction is attained for the 4:2:2 ParkScene sequence, with a reduction of $-11.0\%$. 

In the Random Access tests, the differences in encoding times are marginal. Moreover, moderate decoding time reductions are achieved. The highest encoding time attained is for the 4:2:0 KristenAndSara sequence, with a reduction of $-0.9\%$. A moderate decoding time is attained for the 4:2:2 ParkScene sequence, with a reduction of $-3.4\%$.

The evaluation provides evidence that C-BAQ consistently outperforms AdaptiveQP in terms of coding efficiency and runtime reductions. Recall that AdaptiveQP accounts only for the spatial activity of the four constituent NB×NB sub-blocks of a luma CB in a 2N×2N CU; therefore, the CU level QP is modified on this basis. The proposed C-BAQ technique improves upon AdaptiveQP. This is achieved by accounting for the spatial activity of the constituent sub-blocks of both luma and chroma CBs in the 2N×2N CU, which equates to a more wholesome computation of spatial activity; consequently, a more appropriate CU level QP can be selected. In relation to the input video data utilized in this evaluation, there are regions in all sequences in which the sample activity in each CB (Y, Cb and Cr CBs) differs greatly. That is, certain CUs contain constituent CB sub-blocks in which, for instance, the Y sub-blocks contain high spatial variations, the Cb sub-blocks contain moderate spatial variations and the Cr sub-blocks contain low spatial variations. This disparity of spatial variations between the samples in each CB sub-block is comprehensively acknowledged when computing the QP for the CU as a whole. Compared with accounting for Y CB sub-block spatial activity data only, concurrently accounting for the spatial activity of Y, Cb and Cr data in the corresponding CB sub-blocks evidently results in considerable coding efficiency improvements, as highlighted in Table 1.
A novel CU level adaptive QP technique (C-BAQ) is most effective when applied to 4:4:4 sequences. It is less effective still when applied to 4:2:0 sequences. Consider, for example, the 4:4:4, 4:2:2 and 4:2:0 versions of the ParkScene and Traffic sequences. The results for the 4:4:4 versions of these sequences produce superior results. Furthermore, the results for the 4:2:2 versions of these sequences produce superior results compared with the 4:2:0 versions. Note that the 4:2:0 version has a bit depth of 8-bits per component; both the 4:4:4 and 4:2:2 versions have bit depths of 10-bits per component. Therefore, it appears that the bit depth of the sequence is not a significant factor with respect to the reason why the 4:4:4 and 4:2:2 versions consistently produce superior results. It is reasonable to infer that the subsampled versions of the sequences produce inferior results because downsampled data results in Cb CB and Cr CB size reductions in the corresponding CU. Therefore, assuming that the same input video data is utilized, a smaller CB equates to inferior spatial activity computations with respect to the constituent Cb CB and the Cr CB sub-blocks, thus resulting in the selection of a less appropriate $2^N/2^N$CU level QP.

In the All Intra simulations, C-BAQ attained significant encoding time performance improvements and considerable decoding time reductions (see Fig. 9 and Fig. 10). Furthermore, moderate encoding time and decoding time reductions are achieved in the Random Access tests. When high Y, Cb and Cr spatial activity is detected in a CU, C-BAQ more aggressively quantizes this region in comparison with AdaptiveQP. Therefore, this higher QP selection reduces encoding times. The decreased encoding times attained by C-BAQ are realized because fewer bits need to be encoded due to the higher CU level QP selection in the encoding process.

5. CONCLUSIONS

A novel CU level adaptive QP technique (C-BAQ) is proposed for the HEVC standard to potentially replace the AdaptiveQP tool. We utilized HEVC HM 16.7 to evaluate and compare our method with AdaptiveQP. C-BAQ accounts for the spatial activity of the Y, Cb and Cr samples in the corresponding CB sub-blocks in order to compute a more appropriate $2^N/2^N$ CU level QP. As confirmed in the evaluation, and in comparison with AdaptiveQP, C-BAQ achieves a maximum BD-Rate reduction of 15.9% (Y), 13.1% (Cr) and 16.1% (Cb). Improved encoding times and decoding times are also achieved, with maximum reductions of 6.0% and 11.0%, respectively.

**Fig. 9.** Encoding time improvements of the proposed C-BAQ technique compared with the AdaptiveQP tool on the 4:4:4 8-bit sequence PeopleOnStreet using the Main_444_Intra RExt profile and the All Intra encoding configuration.

**Fig. 10.** Decoding time improvements of the proposed C-BAQ technique compared with the AdaptiveQP tool on the 4:2:2 10-bit sequence ParkScene using the Main_422_10_Intra RExt profile and the All Intra encoding configuration.

**REFERENCES**

[1] A. N. Netravali, N. J. Holmøl and B. Prasad, “Adaptive quantization of picture signals using spatial masking” Proceedings of the IEEE, vol. 65, no. 4, pp. 536-548, 1977.

[2] S. W. Cheadle and S. Zeki, “Masking within and across visual dimensions: Psychophysical evidence for perceptual segregation of color and motion.” Visual Neuroscience, vol. 28, no. 5, pp. 445-451, 2011.

[3] K. McCann, C. Rosewarne, B. Bross, M. Naccari, K. Sharman and G. J. Sullivan (Editors), “High Efficiency Video Coding (HEVC) Test Model 16 (HM 16) Encoder Description”, Document JCTVC-R1002, Sapporo, Japan, 2014.

[4] ITU-T Rec. H.262 | ISO/IEC 13818-2, “Information Technology – Generic coding of moving pictures and associated audio information,” ITU-T/ISO/IEC, 1995.

[5] M. Naccari and M. Mrak, “Intensity Dependent Spatial Quantization with Application in HEVC,” IEEE Int. Conf. Multimedia and Expo, San Jose, CA, 2013, pp. 1-6.

[6] L. Prangnell, V. Sanchez and R. Vanam, “Adaptive Quantization by Soft Thresholding in HEVC,” IEEE Picture Coding Symposium, Queensland, Australia, 2015, pp. 35-39.

[7] G. Sullivan, J-R. Ohm, W. Han and T. Wiegand, “Overview of the High Efficiency Video Coding (HEVC) Standard,” IEEE Trans. Circuits Syst. Video Technol., vol. 22, no. 12, pp. 1649-1668, 2012.

[8] V. Sze, M. Budagavi and G. J. Sullivan, “Block Structures and Parallelism Features in HEVC,” in High Efficiency Video Coding (HEVC): Algorithms and Architecture, Springer International Publishing, 2014, pp. 49-91.

[9] M. Wein, “Coding Structures,” in High Efficiency Video Coding - Coding Tools & Specification, Springer International Publishing, 2015, pp. 101-132.

[10] ITU-T Rec. H.265/HEVC (version 3) | ISO/IEC 23008-2, “Information technology – Coding of audio-visual objects,” ITU-T/ISO/IEC, 2015.

[11] Recommendation ITU-R BT.2020-2 (10/2015), “Parameter values for ultra-high definition television systems for production and international programme exchange,” ITU-R, 2015.

[12] Joint Collaborative Team on Video Coding. JCT-VC HEVC Reference Software, HM 16.7 [Online]. Available: http://hevc.hhi.fraunhofer.de/

[13] F. Bossen, “Common Test Conditions & Software Reference Configurations,” Document JCTVC-L1100, Geneva, 2013, pp. 1-4.

[14] G. Bjontegaard, “Calculation of Average PSNR Differences Between RD-Curves,” Document VCEG-M33, ITU-T Q.6/SG16 VCEG, 2001.