Optimized Dynamic Point Cloud Compression OPT-PCC

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Report on experimental results

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Executive Summary

Point clouds are representations of three-dimensional (3D) objects in the form of a sample of points on their surface. Point clouds are receiving increased attention from academia and industry due to their potential for many important applications, such as real-time 3D immersive telepresence, automotive and robotic navigation, as well as medical imaging. Compared to traditional video technology, point cloud systems allow free viewpoint rendering, as well as mixing of natural and synthetic objects. However, this improved user experience comes at the cost of increased storage and bandwidth requirements as point clouds are typically represented by the geometry and colour (texture) of millions up to billions of 3D points. For this reason, major efforts are being made to develop efficient point cloud compression schemes. However, the task is very challenging, especially for dynamic point clouds (sequences of point clouds), due to the irregular structure of point clouds (the number of 3D points may change from frame to frame, and the points within each frame are not uniformly distributed in 3D space). To standardize point cloud compression (PCC) technologies, the Moving Picture Experts Group (MPEG) launched a call for proposals in 2017. As a result, three point cloud compression technologies were developed: surface point cloud compression (S-PCC) for static point cloud data, video-based point cloud compression (V-PCC) for dynamic content, and LIDAR point cloud compression (L-PCC) for dynamically acquired point clouds. Later, L-PCC and S-PCC were merged under the name geometry-based point cloud compression (G-PCC). The aim of the OPT-PCC project is to develop algorithms that optimise the rate-distortion performance [i.e., minimize the reconstruction error (distortion) for a given bit budget] of V-PCC. The objectives of the project are to:

1. O1: build analytical models that accurately describe the effect of the geometry and colour quantization of a point cloud on the bit rate and distortion;
2. O2: use O1 to develop fast search algorithms that optimise the allocation of the available bit budget between the geometry information and colour information;
3. O3: implement a compression scheme for dynamic point clouds that exploits O2 to outperform the state-of-the-art in terms of rate-distortion performance. The target is to reduce the bit rate by at least 20% for the same reconstruction quality;
4. O4: provide multi-disciplinary training to the researcher in algorithm design, metaheuristic optimisation, computer graphics, media production, and leadership and management skills.

This deliverable reports on the work undertaken in this project to achieve objective O3. The bitrates and distortions were computed for the quantization steps obtained as solutions of the optimization problem for a given target bitrate. Section 1 evaluates the rate-distortion performance of the optimization algorithms developed to achieve objective O2 when the dynamic point cloud consists of one group of frames. Section 2 considers the case when the dynamic point cloud consists of two groups of frames. Each time, two algorithms are evaluated: one where the optimization is carried out with differential evolution (DE) for analytical models of the rate and distortion functions (we call this solution model-based DE solution) and one where the optimization is carried out with DE for the actual rate and distortion functions (we call this solution encoding-based DE solution). To assess the performance of a solution, we compute the Bjøntegaard delta (BD) rate and BD distortion with respect to the state-of-the art method. For the color distortion, we considered only the luminance component. Moreover, we evaluate the bit allocation accuracy by calculating the bitrate error (BE) = $\frac{|R_a - R_T|}{R_a} \times 100\%$, where R_a and R_T are the actual bitrate computed by the method and the target bitrate, respectively. The bitrates are expressed in kilobits per million points (kbpmp). Results are

reported for six dynamic point clouds (*longdress*, *redandblack*, *loot*, *soldier*, *queen*, *basketballplayer*) and for V-PCC Test Model TMC2, which relies on the High Efficiency Video Coding Test Model Version 16. The computer codes used to generate the results are available at http://doi.org/10.5281/zenodo.5034575 and https://doi.org/10.5281/zenodo.5211174 for the one group of frames case and at https://doi.org/10.5281/zenodo.5552760 for the two groups of frames case.

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1 Experimental results for one GOP

1.1 Model-based DE solution

In the DE algorithm [1], the number of iterations and the size of the population were set to 200 and 50, respectively. The range of the scaling factor was [0.1, 0.9]. We used TMC2 v12.0 [2] to encode the first four frames of each point cloud using the IPPP GOP structure and the low delay configuration. The weighting factor ω (see [1], (2)) that sets the relative importance of the geometry distortion and the color distortion was set to 1/2.

Table 1. Bit allocation accuracy and BD [3] performance.

Point cloud	Target bitrate	[6] Bitrate	[6] Distortion	BE	Model-based DE solution Bitrate	Model-based DE solution Distortion	BE	BD Distortion/ BD Color PSNR	BD bitrate/ BD Color bitrate
soldier	65	68.60	27.34	5.54%	63.21	30.59	2.75%	0.79/ -0.20	21.68%/ 9.46%
	125	124.95	18.08	0.04%	126.51	19.12	1.21%		
	165	163.37	15.14	0.99%	174.36	15.56	5.67%		
	210	222.28	12.67	5.85%	213.68	13.69	1.75%		
	265	296.15	10.91	11.75%	275.48	11.87	3.95%		
	365	414.56	9.51	13.58%	375.18	10.20	2.79%		
queen	65	59.87	24.36	7.90%	70.16	23.66	7.93%	0.85/ -0.15	7.9%/ 9.89%
	125	121.09	17.02	3.13%	125.39	17.59	0.32%		
	165	162.14	15.29	1.73%	172.79	15.45	4.72%		
	210	204.88	14.18	2.44%	204.68	14.41	2.54%		
	265	254.58	13.34	3.93%	267.73	13.22	1.03%		
	365	404.43	12.14	10.80%	366.50	12.09	0.41%		
loot	65	62.26	12.60	4.22%	65.26	12.95	0.41%	0.22/ -0.14	9.11% 8.41%
	125	136.61	7.15	9.29%	129.43	7.81	3.54%		
	165	190.11	5.88	15.22%	177.57	6.53	7.62%		
	210	195.26	5.78	7.02%	209.90	5.80	0.05%		
	265	265.31	4.99	0.12%	283.20	5.02	6.87%		
	365	458.86	4.14	25.72%	409.71	4.32	12.25%		
basketballplayer	30	28.97	11.70	3.42%	27.72	12.07	7.61%	-0.10/ 0.04	1.34%/ -1.17
	65	63.53	7.34	2.26%	60.72	7.50	6.58%		
	125	149.71	5.41	19.77%	122.02	5.78	2.38%		
	165	198.11	5.03	20.07%	161.42	5.32	2.17%		
	210	276.95	4.62	31.88%	206.94	4.96	1.46%		
	265	376.71	4.39	42.15%	265.79	4.64	0.30%		
redandblack	90	84.86	18.99	5.71%	83.85	19.83	6.83%	0.02/ -0.03	11.49%/ 2.00%
	180	157.75	11.17	12.36%	162.06	11.24	9.97%		
	270	269.82	8.08	0.07%	253.76	8.47	6.01%		
	360	348.28	6.94	3.25%	361.63	7.02	0.45%		
	480	598.96	5.61	24.78%	520.08	5.93	8.35%		
	640	805.54	5.06	25.87%	737.76	5.19	15.28%		
longdress	180	167.65	47.05	6.86%	157.70	48.20	12.39%	-0.19/ 0.03	-1.11%/ -0.41
	270	307.27	33.70	13.81%	250.05	37.46	7.39%		
	360	424.25	29.52	17.85%	348.55	31.90	3.18%		
	480	597.98	26.07	24.58%	486.96	28.07	1.45%		
	640	784.40	24.15	22.56%	665.42	24.99	3.97%		
	840	1034.7	22.79	23.18%	890.33	22.66	5.99%		
Average				**11.94%**			**4.65%**	**0.27/ -0.08**	**8.40%/ 4.70%**

Table 1 compares the bit allocation accuracy of the proposed method to that of the method in [6]. The point cloud sequences were obtained from [4],[5]. The largest BE for the method in [6] was 42.15% (*basketballplayer*, 265 *kbpmp*), while the largest BE for the proposed method was only 15.28% (*redandblack*, 640 *kbpmp*). Moreover, the average BE for the method in [6] was 11.94%, while that of the proposed method was only 4.65%. Table 1 and Fig. 1 show that the rate-distortion performance of the proposed method is slightly lower than that of the method in [6].

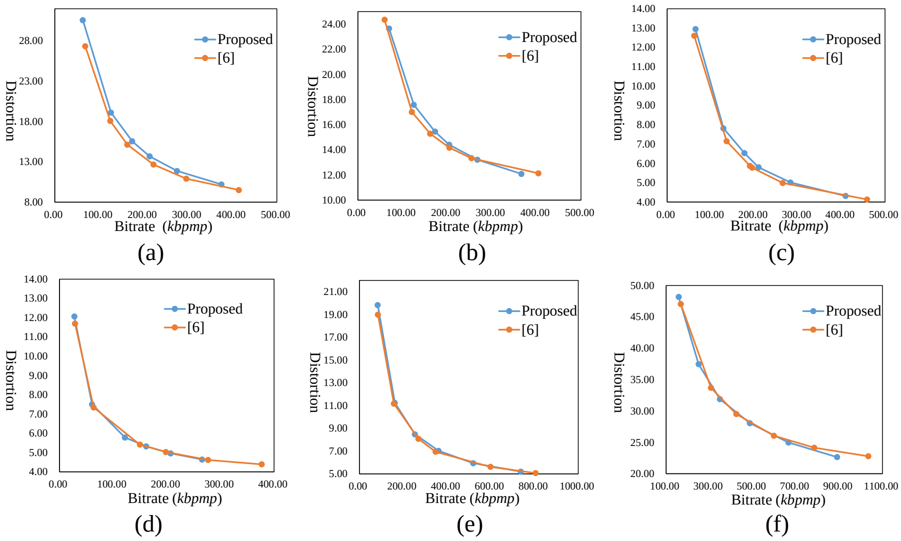

Fig. 1. Rate-distortion curves for the proposed DE-based method and the method in [6]. (a) *soldier*, (b) *queen*, (c) *loot*, (d) *basketballplayer*, (e) *redandblack*, (f) *longdress*.

1.2 Encoding-based DE solution

For the encoding-based DE optimization method [1], we also encoded the first four frames using the low delay configuration with GOP structure IPPP. In the DE algorithm, the size of the population was 50, the number of iterations was 75, and the range of the scaling factor was [0.1, 0.9]. In the initialization step of the DE algorithm, a vector was included only if it satisfied the rate constraint, where the rate was computed according to the proposed analytical model (see [1], Section 3.1). The weighting factor ω was set to 1/2.

Table 2. Rate-distortion performance and bit allocation accuracy. The PSNRs are expressed in dB.

Point cloud	Target bitrate	Method in [6]					Encoding-based DE solution					BD bitrate	BD distortion
		Bitrate	Distortion	PSNR_G	PSNR_C	BE	Bitrate	Distortion	PSNR_G	PSNR_C	BE		
Soldier	65	68.60	27.34	59.13	30.85	5.54%	64.82	24.75	58.62	31.31	0.28%	-30.54%	-0.79
	165	163.37	15.14	62.97	33.40	0.99%	164.90	13.78	63.14	33.81	0.06%		
	265	296.15	10.91	64.38	34.82	11.75%	264.47	10.93	64.86	34.80	0.20%		
	365	414.56	9.51	65.10	35.41	13.58%	364.96	9.55	65.77	35.38	0.01%		
Queen	65	59.87	24.36	63.05	31.30	7.90%	64.98	21.96	63.57	31.75	0.03%	-35.81%	-1.1
	165	162.14	15.29	65.75	33.32	1.73%	163.26	14.41	65.93	33.57	1.06%		
	265	254.58	13.34	65.75	33.92	3.93%	261.94	12.37	66.55	34.24	1.15%		
	365	404.43	12.14	65.75	34.33	10.80%	359.43	11.43	66.76	34.58	1.52%		
Loot	65	62.26	12.60	59.72	34.31	4.22%	64.91	11.32	59.22	34.83	0.13%	-43.04%	-0.19
	165	190.11	5.88	64.27	37.58	15.22%	164.85	6.17	63.98	37.37	0.09%		
	265	265.31	4.99	65.51	38.27	0.12%	262.71	4.90	65.72	38.34	0.86%		
	365	458.86	4.14	65.51	39.11	25.72%	362.57	4.30	66.26	38.91	0.67%		
Longdress	180	167.65	47.05	62.61	28.42	6.86%	179.20	44.26	62.00	28.69	0.45%	-14.59%	-0.79
	360	424.25	29.52	64.62	30.45	17.85%	359.05	31.37	64.76	30.18	0.26%		
	640	784.40	24.15	65.29	31.32	22.56%	639.01	25.07	66.23	31.15	0.15%		
	840	1034.67	22.79	65.29	31.57	23.18%	837.97	22.83	66.66	31.56	0.24%		
Average												**-31%**	**-0.7175**

Table 2 and Fig. 2 compare the rate distortion performance of the encoding-based DE solution to that of the state-of-the-art method [6]. The table provides for various target bitrates, the actual bitrate, the distortion, the peak signal-to-noise ratio (PSNR) for the geometry information (PSNR_G), the PSNR for the color information (PSNR_C), and BE. The PSNR was computed as in [7]. Fig. 2 compares the rate-distortion curves. The results show that our method outperforms the method in [6] in terms of rate-distortion performance and bitrate accuracy. For example, the BD-rate was up to -43.04% and the highest BE was only 1.52%, while it reached 25.72% for the method in [6]. Note that the method in [6] was shown to provide results comparable to exhaustive search subject to the test model zero offset constraint. However, since the method in [6] uses analytical models to solve the optimization problem while the proposed method uses the actual distortion and rate functions, this improvement in rate-distortion performance comes at the cost of increased computation time (Table 3). For the method in [6], the optimization process is very fast but the point cloud must be encoded three times in a pre-processing step to compute the parameters of the rate and distortion models.

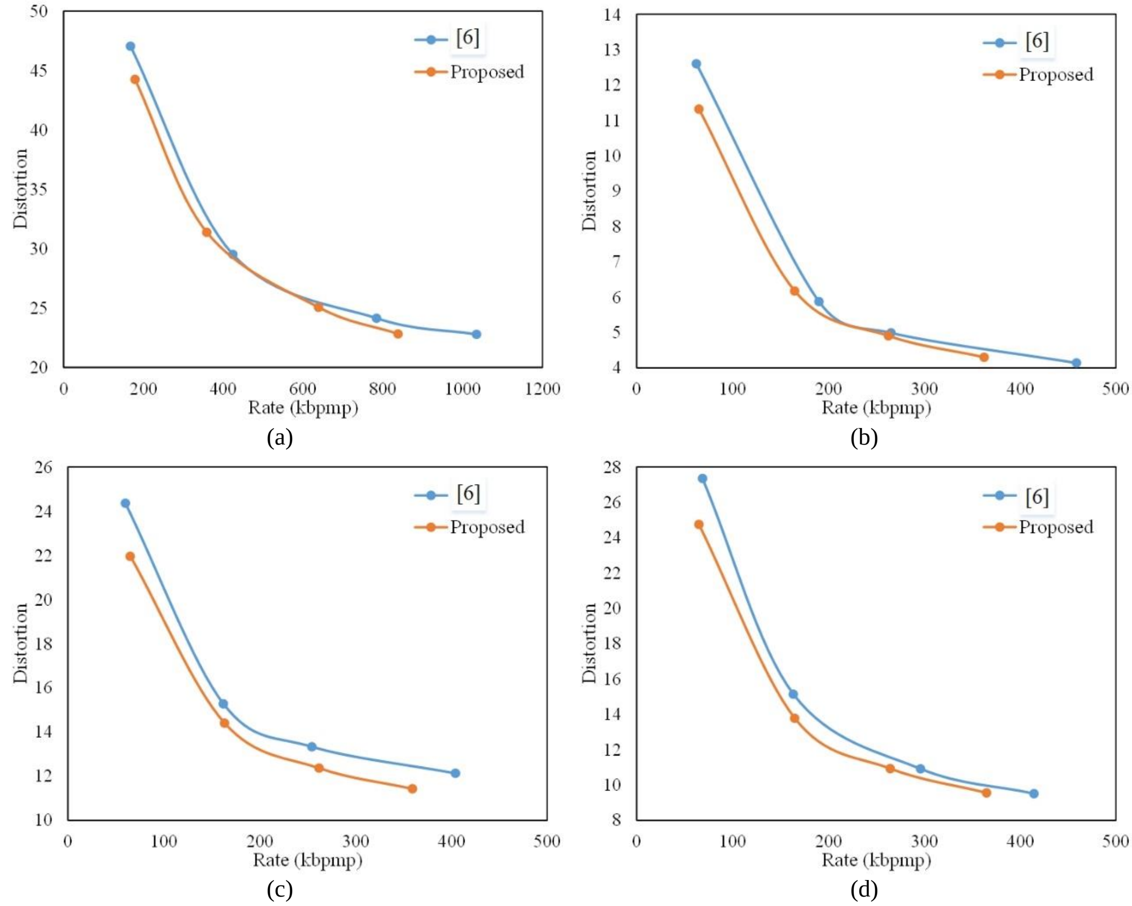

Fig.2. Rate-distortion performance. (a) *Longdress*, (b) *Loot*, (c) *Queen*, (d) *Soldier*.

Table 3. Time complexity comparison. The table shows the number of times the point cloud must be encoded.

Method	initialization	optimization
[6]	3	0
Proposed method	0	76(iterations+1)×50(population size)
Full search	0	52^8

2 Experimental results for two GOPs

2.1 Model-based DE solution

We also verified the performance of the proposed model-based DE method for two groups of frames. In this experiment, the number of iterations and the size of the population in the DE algorithm were set to 3000 and 80, respectively. The range of the scaling factor was also [0.1, 0.9]. To accelerate the encoding for the geometry and color videos, we limited the motion search range to 4, the "MaxPartitionDepth" parameter to 1, and the transform size to 16 in the configuration file of the HEVC encoder.

We encoded the first eight frames of the point clouds using the IPPP GOP structure and the low delay configuration, where the GOP size was equal to 4. As the two GOPs are taken as a whole, the DE algorithm computes eight quantization parameters for the geometry and color videos, respectively (that is, the number of variables in the optimization problem is 16).

The results are given in Table 4. The RD performance of the model-based DE solution was worse than that of the state-of-the-art method [6]. The BE performance was also worse (5.12% for the model-based DE solution vs. 4.45% for the method in [6]). Compared to the one-GOP case, the estimation errors of the rate and distortion models are increased due to the increased number of frames.

Table 4. Bit allocation accuracy and BD performance.

Point cloud	Target bitrate	[6]		BE	Model-based DE solution		BE	BD Distortion	BD bitrate
		Bitrate	Distortion		Bitrate	Distortion			
soldier	65	65.56	32.93	0.87%	68.95	34.55	6.08%	1.48	10.00%
	125	130.78	18.64	4.63%	129.98	20.37	3.99%		
	165	154.20	16.32	6.55%	178.09	15.68	7.93%		
	210	204.24	12.91	2.74%	213.88	13.36	1.85%		
	265	267.17	10.36	0.82%	285.59	10.52	7.77%		
	365	366.52	7.97	0.42%	378.61	8.20	3.73%		
queen	65	66.27	27.79	1.96%	64.32	28.56	1.04%	0.21	2.47%
	125	115.74	19.53	7.40%	118.66	19.57	5.07%		
	165	147.04	17.13	10.88%	153.08	16.83	7.22%		
	210	192.95	14.83	8.12%	191.80	15.13	8.66%		
	265	248.82	13.02	6.10%	252.85	13.06	4.58%		
	365	315.84	11.57	13.47%	355.36	11.09	2.64%		
loot	65	65.85	13.50	1.31%	71.54	14.10	10.06%	0.62	9.43%
	125	130.93	7.52	4.74%	131.85	8.09	5.48%		
	165	170.08	6.01	3.08%	178.13	6.18	7.96%		
	210	204.22	5.12	2.75%	219.00	5.19	4.28%		
	265	270.83	4.09	2.20%	274.85	4.26	3.72%		
	365	372.58	3.20	2.08%	384.54	3.24	5.35%		
basketballplayer	30	29.39	12.86	2.04%	29.86	13.57	0.46%	0.17	4.62%
	65	62.67	7.42	3.59%	60.40	7.74	7.07%		
	125	132.00	5.03	5.60%	125.85	5.21	0.68%		
	165	181.86	4.36	10.22%	176.33	4.44	6.86%		
	210	218.11	4.02	3.86%	234.01	3.91	11.44%		
	265	310.19	3.45	17.05%	310.03	3.45	16.99%		
redandblack	90	90.41	21.04	0.45%	88.14	22.37	2.07%	0.38	6.95%
	180	170.58	11.67	5.23%	169.50	12.39	5.83%		
	270	257.45	8.77	4.65%	261.14	8.89	3.28%		
	360	366.55	6.55	1.82%	348.56	6.87	3.18%		
	480	495.56	5.28	3.24%	496.02	5.34	3.34%		
	640	669.34	4.22	4.58%	698.81	4.18	9.19%		
longdress	180	176.41	53.52	1.99%	173.90	53.77	3.39%	0.026	0.24%
	270	264.37	38.24	2.08%	260.43	39.11	3.54%		
	360	354.53	30.37	1.52%	342.04	31.10	4.99%		
	480	496.46	23.90	3.43%	484.42	24.41	0.92%		
	640	671.52	18.76	4.92%	653.84	19.22	2.16%		
	840	871.50	15.20	3.75%	851.30	15.36	1.35%		
	Average			**4.45%**			**5.12%**	**0.481**	**5.62%**

To decrease the BE of the model-based DE solution, we modified the objective function (equation (2) in [1]) by including the standard deviation of the geometry frames and color frames:

$$\min_{\boldsymbol{Q}_g,\boldsymbol{Q}_c} 0.1 \times D(\boldsymbol{Q}_g,\boldsymbol{Q}_c) + 0.9 \times S_{td}(\boldsymbol{Q}_g,\boldsymbol{Q}_c) \quad (1)$$
$$s.t. \quad R(\boldsymbol{Q}_g,\boldsymbol{Q}_c) \leq R_T,$$

where $\boldsymbol{Q}_g$ represents the geometry quantization steps, $\boldsymbol{Q}_c$ represents the color quantization steps, $D(\boldsymbol{Q}_g,\boldsymbol{Q}_c) = \omega D_c(\boldsymbol{Q}_g,\boldsymbol{Q}_c) + (1-\omega)D_g(\boldsymbol{Q}_g,\boldsymbol{Q}_c)$ represents the weighted average of the color distortion and geometry distortion, and $S_{td}(\boldsymbol{Q}_g,\boldsymbol{Q}_c)$ represents the standard deviation of the distortion. Table 5 shows the results. We can see that by taking the standard deviation into account, the BE (2.86%) of the model-based DE solution decreased significantly and is now lower than that of the method in [6]. This shows that the fluctuation of the quantization parameters of the frames can be reduced by adding the standard deviation.

Table 5. Bit allocation accuracy and BD performance.

Point cloud	Target bitrate	[6]		BE	Model-based DE solution		BE	BD Distortion	BD bitrate
		Bitrate	Distortion		Bitrate	Distortion			
soldier	65	65.56	32.93	0.87%	63.23	33.92	2.72%	0.35	1.23%
	125	130.78	18.64	4.63%	126.85	19.51	1.48%		
	165	154.20	16.32	6.55%	166.84	15.76	1.12%		
	210	204.24	12.91	2.74%	206.90	13.18	1.48%		
	265	267.17	10.36	0.82%	275.41	10.83	3.93%		
	365	366.52	7.97	0.42%	375.64	8.05	2.92%		
queen	65	66.27	27.79	1.96%	64.09	28.44	1.41%	1.05	8.97%
	125	115.74	19.53	7.40%	120.81	19.71	3.35%		
	165	147.04	17.13	10.88%	165.54	17.30	0.33%		
	210	192.95	14.83	8.12%	219.01	15.47	4.29%		
	265	248.82	13.02	6.10%	277.98	14.08	4.90%		
	365	315.84	11.57	13.47%	388.00	12.20	6.30%		
loot	65	65.85	13.50	1.31%	64.49	13.93	0.79%	0.15	2.49%
	125	130.93	7.52	4.74%	127.76	7.91	2.21%		
	165	170.08	6.01	3.08%	166.24	6.26	0.75%		
	210	204.22	5.12	2.75%	207.93	5.16	0.98%		
	265	270.83	4.09	2.20%	264.40	4.19	0.23%		
	365	372.58	3.20	2.08%	351.64	3.36	3.66%		
basketballplayer	30	29.39	12.86	2.04%	29.52	13.29	1.59%	0.14	3.83%
	65	62.67	7.42	3.59%	61.92	7.60	4.75%		
	125	132.00	5.03	5.60%	124.85	5.24	0.12%		
	165	181.86	4.36	10.22%	176.24	4.51	6.81%		
	210	218.11	4.02	3.86%	235.08	3.96	11.94%		
	265	310.19	3.45	17.05%	273.80	3.71	3.32%		
redandblack	90	90.41	21.04	0.45%	87.49	22.90	2.79%	0.43	9.63%
	180	170.58	11.67	5.23%	165.28	12.46	8.18%		
	270	257.45	8.77	4.65%	259.03	8.89	4.06%		
	360	366.55	6.55	1.82%	360.25	6.83	0.07%		
	480	495.56	5.28	3.24%	491.39	5.53	2.37%		
	640	669.34	4.22	4.58%	686.00	4.69	7.19%		
longdress	180	176.41	53.52	1.99%	173.89	53.94	3.40%	0.80	3.79%
	270	264.37	38.24	2.08%	268.55	38.42	0.54%		
	360	354.53	30.37	1.52%	356.12	33.16	1.08%		
	480	496.46	23.90	3.43%	487.25	24.26	1.51%		
	640	671.52	18.76	4.92%	638.82	19.63	0.18%		
	840	871.50	15.20	3.75%	840.23	15.71	0.03%		
Average				**4.45%**			**2.86%**	**0.49**	**4.99%**

2.2 Encoding-based DE solution

We also applied the encoding-based DE solution to the two-GOP case. We encoded the first eight frames using the low delay configuration with GOP structure IPPP. In the DE algorithm, the size of the population was 80, the number of iterations was 150, and the range of the scaling factor was the interval [0.1, 0.9]. In the initialization step, a vector was included only if it satisfied the rate constraint, where the rate was computed according to the proposed analytical model. The weighting factor ω was set to 1/2. To accelerate the encoding procedure for the geometry and color videos, as in Section 2.1, we limited the motion search range to 4, “MaxPartitionDepth” to 1, and the transform size to 16 in the configuration file of the HEVC encoder.

Table 6. Bit allocation accuracy and BD performance.

Point cloud	Target bitrate	[6]		BE	Encoding-based DE solution		BE	BD Distortion	BD bitrate
		Bitrate	Distortion		Bitrate	Distortion			
soldier	65	65.56	32.93	0.87%	64.83	29.94	0.04%	-1.30	-10.15%
	125	130.78	18.64	4.63%	124.66	17.80	0.08%		
	165	154.20	16.32	6.55%	164.32	14.49	0.41%		
	210	204.24	12.91	2.74%	209.70	11.81	0.13%		
	265	267.17	10.36	0.82%	264.28	9.79	0.20%		
	365	366.52	7.97	0.42%	364.68	7.67	0.49%		
queen	65	66.27	27.79	1.96%	64.94	26.81	0.10%	-0.52	-5.64%
	125	115.74	19.53	7.40%	124.88	18.24	0.09%		
	165	147.04	17.13	10.88%	164.24	15.73	0.46%		
	210	192.95	14.83	8.12%	209.28	13.96	0.34%		
	265	248.82	13.02	6.10%	263.89	12.42	0.42%		
	365	315.84	11.57	13.47%	362.66	10.45	0.64%		
loot	65	65.85	13.50	1.31%	64.99	12.67	0.01%	-0.37	-7.05%
	125	130.93	7.52	4.74%	124.86	7.45	0.25%		
	165	170.08	6.01	3.08%	164.74	5.89	0.24%		
	210	204.22	5.12	2.75%	209.94	4.85	0.06%		
	265	270.83	4.09	2.20%	264.92	4.07	0.17%		
	365	372.58	3.20	2.08%	361.94	3.26	2.57%		
redandblack	90	90.41	21.04	0.45%	89.61	20.71	0.43%	-0.01	2.13%
	180	170.58	11.67	5.23%	178.55	11.55	0.81%		
	270	257.45	8.77	4.65%	269.22	8.30	0.29%		
	360	366.55	6.55	1.82%	360.00	6.56	0.00%		
	480	495.56	5.28	3.24%	479.71	5.37	0.06%		
	640	669.34	4.22	4.58%	639.84	4.36	0.03%		
longdress	180	176.41	53.52	1.99%	179.98	50.87	0.01%	-0.68	-2.76%
	270	264.37	38.24	2.08%	269.69	37.03	0.12%		
	360	354.53	30.37	1.52%	359.99	29.42	0.00%		
	480	496.46	23.90	3.43%	479.81	23.84	0.04%		
	640	671.52	18.76	4.92%	639.95	19.25	0.01%		
	840	871.50	15.20	3.75%	839.36	15.30	0.08%		
Average				**4.45%**			**0.29%**	**-0.58**	**-4.69%**

Table 6 compares the rate-distortion performance of the encoding-based DE solution to that of the state-of-the-art method [6]. The results show that the proposed method outperforms the method in [6] in terms of rate-distortion performance and bitrate accuracy. For example, the BD-rate was up to -10.15% and the average BE was only 0.29%, while it reached 4.45% for the method in [6]. Because the video encoder configuration for the two-GOP case was simplified to reduce the encoding time, the potential gain of the proposed solution for the two-GOP case is smaller than that for the one- GOP one. For this reason, the gains shown in Table 6 are smaller than those shown in Table 2.

3 References

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