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Abstract

This document complements the study presented in the report EE4FE 13.40 on improving RAHT in terms of low complexity. More specifically, it includes the comparison of (a) *Haar* vs. *fastHaar*; and (b) *predlift* vs. *fastRAHT* and *fastHaar*. Experiments also include *qpChormaOffet* variation and coordinate scaling for *fastRAHT* and *fastHaar*. Octree and predictive geometry are used as geometry coders. Results show that: (a) *fastRAHT* and *fastHaar* outperform other transforms in terms of runtimes; (b) in some configurations outperform other transforms also in terms of coding efficiency; and (c) coding losses may be considered tolerable if reduction in runtimes is targeted.

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1. Introduction

In the EE4FE 13.40 [1], [2], [3] authors show evidences that using the original fixed-point RAHT implementation of TMC13v6 [4] offers the possibility of low-complexity attribute coding for category 3 (cat3-fused and cat3-frame) sequences under C1 and C2 conditions. The anchor for the study was the TMC13v10 RAHT implementation, but comparison against *predlift* was not included. In the current contribution, *predlift* is also used as anchor and the non-adopted lossless *Haar* and *fastHaar* transforms proposed in [5] and [6], respectively, are evaluated as well.

In the last MPEG meeting, several documents concerning profiles were submitted and discussed [7], [8], [9], [10], [11]. One of the possible profiles described in these

documents is the "automotive profile", represented by the same category 3 point cloud set studied in the EE4FE 13.40. The main goal of the current contribution is to extend the results presented in this EE4FE report and verify if *fastRAHT* [4] and *fastHaar* [6] can be used as competitive attribute transforms for the "automotive profile."

The description of each attribute transform explored in the current study is presented in the Table 1. The *predlift* transform and *RAHT* (On and Off) are part of the current test model TMC13v11.0. *Haar* (On and Off) and *fastHaar* are non-adopted proposals. And *fastRAHT* is a previous implementation of RAHT that ceased to be used since TMC13v7.0.

Coordinate scaling [5] and *qpChromaOffset* different than 0 also also used, when applicable.

Transform	Description
predlift	TMC13v11 *predlift* [11]
RAHTOn	TMC13v11 *RAHT* with prediction enabled [11]
RAHTOff	TMC13v11 *RAHT* with prediction disabled [11]
HaarOn	TMC13v10 lossless *Haar* proposal [4], implemented on top of TMC13v11 with prediction enabled
HaarOff	TMC13v10 lossless *Haar* proposal [4], implemented on top of TMC13v11 with prediction disabled
fastRAHT	TMC13v6 *RAHT* [3], implemented on top of TMC13v11
fastHaar	TMC13v6 lossless *Haar* proposal [5], implemented on top of TMC13v11

Table 1: Description of the evaluated attribute transforms.

In the next section, experiments are described and experimental results are presented.

2. Experiments

The coding performance and runtimes of the attribute transforms previously described are evaluated. The experiments are distributed in two main groups, one that uses octree and the other that uses predictive geometry as geometry coders. These two groups of experiments are described in Sections2.1 and 2.2, respectively.

2.1. Attribute transforms + Octree

In this group of experiments, octree coding is applied with *sliceMinPoints* and *sliceMaxPoints* equal to 550000 and 1100000, respectively, as in the CTC. Simulations for conditions C1, C2 and CW are made according to Table 2. Category 3 (cat3-fused and cat3-frame) point clouds compose the test set.

Octree			Tested	
		vs.	*fastRAHT*	*fastHaar*
Reference	(a)	*RAHTOn*	C1, C2	---
	(b)	*HaarOn*	---	CW
	(c)	*RAHTOff*	C1, C2	---
	(d)	*HaarOff*	---	CW
	(e)	*predlift*	C1, C2	CW

Table 2: Comparison between attribute transforms.

Predlift simulations are performed according to the CTC. Regarding *fastRAHT*/*fastHaar*, the following additional parameters are also taken into consideration:

a) Encoder-side inverse transform enabled/disabled [2]. Applied to C1, C2 and CW, from (a) to (e);
b) *qpChromaOffset* = 0 and -1 [13]. Applied to C1 and C2 of (e); and
c) Coordinate scaling [5] with *rahtScaleShift* = $\{0, 0, 0\}$ and $\{4, 4, 4\}$. Applied to C1, C2 and CW of (e).

Summarized results are shown in Sections2.1.1 and 2.1.2.

2.1.1. *Octree-RAHT/Haar vs. -fastRAHT/Haar*

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]				
	Luma	Chroma Cb	Chroma Cr	Reflectance	
Cat3-fused average	6.4%	6.0%	6.1%	9.9%	1
Cat3-frame average				2.9%	
	6.4%	6.0%	6.1%	9.9%	2
				2.9%	
	2.3%	2.2%	2.1%	2.9%	3
				1.5%	

1: **RAHTOn** vs. fastRAHT **encoder-side decoder enable**
2: **RAHTOn** vs. fastRAHT **encoder-side decoder disabled**
3: **RAHTOff** vs. fastRAHT **encoder-side decoder disabled**

	1	2	3
Avg. Enc Time [%]	57%	47%	58%
Avg. Dec Time [%]	50%	50%	64%
Avg. Col. Enc Time [%]	50%	22%	32%
Avg. Col. Dec Time [%]	30%	31%	48%
Avg. Ref. Enc Time [%]	27%	14%	20%
Avg. Ref. Dec Time [%]	20%	20%	31%
Avg. Geo. Enc Time [%]	105%	103%	98%
Avg. Geo. Dec Time [%]	105%	104%	98%

(a) C1: RAHT vs. fastRAHT

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]				
	Luma	Chroma Cb	Chroma Cr	Reflectance	
Cat3-fused average	12.3%	9.0%	8.9%	14.8%	1
Cat3-frame average				3.9%	
	12.3%	9.0%	8.9%	14.8%	2
				3.9%	
	3.9%	2.4%	2.4%	4.0%	3
				0.8%	

1: **RAHTOn** vs. fastRAHT **encoder-side decoder enable**
2: **RAHTOn** vs. fastRAHT **encoder-side decoder disabled**
3: **RAHTOff** vs. fastRAHT **encoder-side decoder disabled**

	1	2	3
Avg. Enc Time [%]	80%	76%	84%
Avg. Dec Time [%]	48%	48%	67%
Avg. Col. Enc Time [%]	36%	20%	36%
Avg. Col. Dec Time [%]	22%	22%	47%
Avg. Ref. Enc Time [%]	23%	12%	21%
Avg. Ref. Dec Time [%]	16%	16%	31%
Avg. Geo. Enc Time [%]	103%	101%	97%
Avg. Geo. Dec Time [%]	101%	100%	96%

(b) C2: RAHT vs. fastRAHT

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]				
	Geometry	Colour	Reflectance	Total	
Cat3-fused average	100.0%	98.3%	100.1%	99.4%	1
Cat3-frame average	100.0%		100.3%	100.1%	
	100.0%	98.3%	100.1%	99.4%	2
	100.0%		100.3%	100.1%	
	100.0%	98.3%	100.4%	99.4%	3
	100.0%		100.4%	100.1%	

1: **HaarOn** vs. fastHaar **encoder-side decoder enable**
2: **HaarOn** vs. fastHaar **encoder-side decoder disabled**
3: **HaarOff** vs. fastRAHT **encoder-side decoder disabled**

	1	2	3
Avg. Enc Time [%]	63%	52%	65%
Avg. Dec Time [%]	58%	55%	68%
Avg. Col. Enc Time [%]	39%	23%	22%
Avg. Col. Dec Time [%]	32%	29%	28%
Avg. Ref. Enc Time [%]	29%	17%	29%
Avg. Ref. Dec Time [%]	24%	23%	40%
Avg. Geo. Enc Time [%]	107%	100%	100%
Avg. Geo. Dec Time [%]	107%	101%	101%

(c) CW: Haar vs. fastHaar

Table 3: Comparison of RAHT vs. fastRAHT (C1, C2) and Haar vs. fastHaar (CW).

2.1.2. *Octree-predlift vs. -fastRAHT/Haar*

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]				
	Luma	Chroma Cb	Chroma Cr	Reflectance	
Cat3-fused average	-7.2%	0.5%	0.4%	0.8%	1
Cat3-frame average				-3.5%	
	-7.2%	0.5%	0.4%	0.8%	2
				-3.5%	
	-4.0%	-6.8%	-6.6%	0.8%	3
				-3.5%	
	-3.8%	-6.6%	-6.4%	1.0%	4
				-3.9%	

predlift = CTC
1: fastRAHT **encoder-side decoder enabled**, qpChromaOffset = 0
2: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = 0
3: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1
4: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1

scaleShift
{0, 0, 0}
{4, 4, 4}

	1	2	3	4
Avg. Enc Time [%]	88%	72%	72%	68%
Avg. Dec Time [%]	77%	77%	76%	69%
Avg. Col. Enc Time [%]	105%	47%	45%	31%
Avg. Col. Dec Time [%]	63%	63%	61%	35%
Avg. Ref. Enc Time [%]	105%	54%	53%	43%
Avg. Ref. Dec Time [%]	83%	82%	83%	57%
Avg. Geo. Enc Time [%]	97%	96%	96%	96%
Avg. Geo. Dec Time [%]	97%	97%	97%	96%

(a) C1: predlift vs. fastRAHT

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]				
	Luma	Chroma Cb	Chroma Cr	Reflectance	
Cat3-fused average	-8.3%	3.5%	5.0%	-1.1%	1
Cat3-frame average				-7.4%	
	-8.3%	3.5%	5.0%	-1.1%	2
				-7.4%	
	-5.5%	-4.6%	-3.5%	-1.1%	3
				-7.4%	
	-5.5%	-4.6%	-3.4%	-1.1%	4
				-7.4%	

predlift = CTC
1: fastRAHT **encoder-side decoder enabled**, qpChromaOffset = 0
2: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = 0
3: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1
4: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1

scaleShift
{0, 0, 0}
{4, 4, 4}

	1	2	3	4
Avg. Enc Time [%]	91%	86%	86%	85%
Avg. Dec Time [%]	73%	72%	71%	71%
Avg. Col. Enc Time [%]	56%	31%	31%	30%
Avg. Col. Dec Time [%]	36%	35%	35%	32%
Avg. Ref. Enc Time [%]	76%	41%	41%	39%
Avg. Ref. Dec Time [%]	59%	58%	58%	56%
Avg. Geo. Enc Time [%]	98%	96%	96%	95%
Avg. Geo. Dec Time [%]	98%	97%	96%	96%

(b) C2: predlift vs. fastRAHT

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]				
	Geometry	Colour	Reflectance	Total	
Cat3-fused average	100.0%	106.4%	106.5%	103.1%	1
Cat3-frame average	100.0%		106.6%	101.3%	
	100.0%	106.4%	106.5%	103.1%	2
	100.0%		106.6%	101.3%	
	100.0%	106.6%	106.5%	103.2%	3
	100.0%		106.1%	101.2%	

predlift = CTC
1: fastHaar **encoder-side decoder enabled**
2: fastHaar **encoder-side decoder disabled**
3: fastHaar **encoder-side decoder disabled**

scaleShift
{0, 0, 0}
{4, 4, 4}

	1	2	3
Avg. Enc Time [%]	82%	68%	66%
Avg. Dec Time [%]	73%	69%	65%
Avg. Col. Enc Time [%]	55%	32%	24%
Avg. Col. Dec Time [%]	41%	36%	26%
Avg. Ref. Enc Time [%]	86%	49%	41%
Avg. Ref. Dec Time [%]	69%	67%	52%
Avg. Geo. Enc Time [%]	104%	97%	98%
Avg. Geo. Dec Time [%]	104%	98%	98%

(c) CW: predlift vs. fastHaar

Table 4: Comparison of octree-predlift vs. -fastRAHT (C1, C2) and -predlift vs. -fastHaar (CW) for different simulation setups.

2.2. *Attribute transforms + Predictive geometry*

Here, predictive geometry is used and two sets of experiments are performed. The first set uses *predGeomTreePtsMax* equal to 1100000, as specified in the CTC, and in the second one, *predGeomTreePtsMax* is adjusted to 512. Simulations for conditions C1, C2 and CW are made according to Table 5. Category 3 (cat3-fused and cat3-frame) point clouds compose the test set.

PredGeom		Tested	
	vs.	*fastRAHT*	*fastHaar*
Ref.	*predlift*	C1, C2	CW

Table 5: Comparison between attribute transforms.

Predlift simulations are performed according to the CTC. Regarding *fastRAHT and fastHaar*, the following additional parameters are also taken into consideration:

a) Encoder-side inverse transform disabled. Applied to C1, C2 and CW.
b) *qpChromaOffset* = 0 and -1. Applied to C1 and C2.
c) Coordinate scaling with *rahtScaleShift* = $\{0, 0, 0\}$ and $\{4, 4, 4\}$. Applied to C1, C2 and CW.

Summarized results are show in Sections Table 6.

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]				
	Luma	Chroma Cb	Chroma Cr	Reflectance	
Cat3-fused average	-7.2%	0.5%	0.4%	0.8%	1
Cat3-frame average				-3.4%	
	-7.2%	0.5%	0.4%	0.8%	2
				-3.4%	
	-4.0%	-6.8%	-6.6%	0.8%	3
				-3.4%	
	-3.8%	-6.6%	-6.4%	1.0%	4
				-3.8%	
	-3.8%	-6.7%	-6.5%	1.0%	5
				-3.9%	

	1	2	3	4	5
Avg. Enc Time [%]	91%	84%	81%	85%	80%
Avg. Dec Time [%]	54%	53%	58%	47%	46%
Avg. Col. Enc Time [%]	74%	36%	41%	30%	27%
Avg. Col. Dec Time [%]	48%	46%	70%	40%	37%
Avg. Ref. Enc Time [%]	85%	46%	49%	37%	39%
Avg. Ref. Dec Time [%]	70%	69%	79%	53%	54%
Avg. Geo. Enc Time [%]	103%	103%	98%	97%	98%
Avg. Geo. Dec Time [%]	103%	101%	96%	101%	97%

scaleShift

1: fastRAHT **encoder-side decoder enabled**, qpChromaOffset = 0, PtsMax = 512
2: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = 0, PtsMax = 512 — {0, 0, 0}
3: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1, PtsMax = 512
4: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1, PtsMax = CTC
5: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1, PtsMax = 512 — {4, 4, 4}

(a) C1: predlift vs. fastRAHT

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]				
	Luma	Chroma Cb	Chroma Cr	Reflectance	
Cat3-fused average	-9.9%	3.6%	4.4%	-0.2%	1
Cat3-frame average				-8.1%	
	-9.9%	3.6%	4.4%	-0.2%	2
				-8.1%	
	-7.0%	-4.3%	-3.8%	-0.2%	3
				-8.1%	
	-7.0%	-4.3%	-3.8%	-0.2%	4
				-8.1%	
	-7.0%	-4.3%	-3.8%	-0.2%	5
				-8.1%	

	1	2	3	4	5
Avg. Enc Time [%]	94%	89%	93%	85%	91%
Avg. Dec Time [%]	62%	62%	62%	63%	60%
Avg. Col. Enc Time [%]	113%	55%	60%	55%	54%
Avg. Col. Dec Time [%]	75%	74%	78%	78%	74%
Avg. Ref. Enc Time [%]	99%	51%	51%	50%	49%
Avg. Ref. Dec Time [%]	82%	83%	84%	86%	79%
Avg. Geo. Enc Time [%]	98%	97%	101%	83%	100%
Avg. Geo. Dec Time [%]	102%	93%	84%	105%	93%

scaleShift

1: fastRAHT **encoder-side decoder enabled**, qpChromaOffset = 0, PtsMax = 512
2: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = 0, PtsMax = 512 — {0, 0, 0}
3: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1, PtsMax = 512
4: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1, PtsMax = CTC
5: fastRAHT **encoder-side decoder disabled**, qpChromaOffset = -1, PtsMax = 512 — {4, 4, 4}

(b) C2: predlift vs. fastRAHT

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]				
	Geometry	Colour	Reflectance	Total	
Cat3-fused average	100.0%	106.4%	106.5%	103.1%	1
Cat3-frame average	100.0%		106.6%	101.3%	
	100.0%	106.4%	106.5%	103.1%	2
	100.0%		106.6%	101.3%	
	100.0%	106.6%	106.5%	103.5%	3
	100.0%		106.1%	101.3%	
	100.0%	106.6%	106.5%	103.2%	4
	100.0%		106.1%	101.2%	

scaleShift

1: fastHaar **encoder-side decoder enabled,** PtsMax = 512
2: fastHaar **encoder-side decoder disabled,** PtsMax = 512 — {0, 0, 0}
3: fastHaar **encoder-side decoder disabled,** PtsMax = 1100000 (CTC)
4: fastHaar **encoder-side decoder disabled,** PtsMax = 512 — {4, 4, 4}

	1	2	3	4
Avg. Enc Time [%]	85%	81%	79%	80%
Avg. Dec Time [%]	51%	51%	47%	45%
Avg. Col. Enc Time [%]	48%	29%	23%	23%
Avg. Col. Dec Time [%]	36%	35%	27%	26%
Avg. Ref. Enc Time [%]	82%	49%	44%	41%
Avg. Ref. Dec Time [%]	67%	68%	56%	52%
Avg. Geo. Enc Time [%]	98%	98%	88%	99%
Avg. Geo. Dec Time [%]	98%	96%	106%	98%

(c) CW: predlift vs. fastHaar

Table 6: Comparison of predgeom predlift vs. fastRAHT (C1 and C2) and predlift vs. fastHaar (CW).

3. Conclusion

The conclusions are drawn having the "automotive profile" as target. If lossless attribute and lossless geometry coding is required, there are three possible scenarios: (1) *octree-haar* is the reference. In this case, Table 3(c) shows that *octree-fastHaar* offers comparable coding performance (less than 1% losses) with reduced average encoding (between 52% and 65%) and decoding (between 55% and 68%) runtimes considering different simulation scenarios; (2) *octree-predlift* is the reference. The observed losses of *octree-fastHaar* in relation to *predlift* are up to 7% in terms of bpip. However, average encoding (between 66% and 82%) and decoding (between 65% and 73%) runtimes are significantly reduced, as shown in Tables 7; and (3) *predgeom-predlift* is the reference. In this case, the losses of *octree-fastHaar* in relation to *predlift* are also up to 7% in terms of bpip. However, average encoding (between 79% and 85%) and decoding (between 45% and 51%) runtimes are reduced, as shown in Tables 8.

If lossy attribute coding is allowed, then Tables 7 and 8 show summarized results for the best and worst case scenario of octree-predlift vs. -fastRAHT/Haar and predgeom-predlift vs. -fastRAHT/Haar. In some configurations one may notice that *fastRAHT* and *fastHaar* not only offers better runtimes, but also better encoding performance.

Given these results, one may conclude that *fastRAHT* and *fastHaar* represent competitive attribute transform implementations in the context of the "automotive profile". Finally, it's important to say that *fastHaar* represents a simplification of *fastRAHT*. From the implementation point of view, if the *fastRAHT* kernel is implemented, enabling *fastHaar* is achieved by imposing some minor conditions.

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
Cat3-fused average	-7.2%	0.5%	0.4%	0.8%
Cat3-frame average				-3.5%

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
	-8.3%	3.5%	5.0%	-1.1%
				-7.4%

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]			
	Geometry	Colour	Reflectance	Total
	100.0%	106.4%	106.5%	103.1%
	100.0%		106.6%	101.3%

	C1	C2	CW
Avg. Enc Time [%]	88%	91%	82%
Avg. Dec Time [%]	77%	73%	73%
Avg. Col. Enc Time [%]	105%	56%	55%
Avg. Col. Dec Time [%]	63%	36%	41%
Avg. Ref. Enc Time [%]	105%	76%	86%
Avg. Ref. Dec Time [%]	83%	59%	69%
Avg. Geo. Enc Time [%]	97%	98%	104%
Avg. Geo. Dec Time [%]	97%	98%	104%

fastRAHT/Haar **encoder-side decoder enabled**, qpChromaOffset = 0, scaleShift = {0, 0, 0}

(a) octree-predlift vs. -fastRAHT and -fastHaar, worst case scenario.

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
Cat3-fused average	-3.8%	-6.6%	-6.4%	1.0%
Cat3-frame average				-3.9%

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
Cat3-fused average	-5.5%	-4.6%	-3.4%	-1.1%
Cat3-frame average				-7.4%

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]			
	Geometry	Colour	Reflectance	Total
Cat3-fused average	100.0%	106.6%	106.5%	103.2%
Cat3-frame average	100.0%		106.1%	101.2%

	C1	C2	CW
Avg. Enc Time [%]	68%	85%	66%
Avg. Dec Time [%]	69%	71%	65%
Avg. Col. Enc Time [%]	31%	30%	24%
Avg. Col. Dec Time [%]	35%	32%	26%
Avg. Ref. Enc Time [%]	43%	39%	41%
Avg. Ref. Dec Time [%]	57%	56%	52%
Avg. Geo. Enc Time [%]	96%	95%	98%
Avg. Geo. Dec Time [%]	96%	96%	98%

FastRAHT/Haar **encoder-side decoder disabled**, qpChromaOffset = -1, scaleShift = {4, 4, 4}

(b) octree predlift vs. fastRAHT and fastHaar, best case scenario.

Table 7: Comparison of octree- predlift vs. fastRAHT and. fastHaar.

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
Cat3-fused average	-7.2%	0.5%	0.4%	0.8%
Cat3-frame average				-3.4%

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
	-9.9%	3.6%	4.4%	-0.2%
				-8.1%

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]			
	Geometry	Colour	Reflectance	Total
	100.0%	106.4%	106.5%	103.1%
	100.0%		106.6%	101.3%

C1	
Avg. Enc Time [%]	91%
Avg. Dec Time [%]	54%
Avg. Col. Enc Time [%]	74%
Avg. Col. Dec Time [%]	48%
Avg. Ref. Enc Time [%]	85%
Avg. Ref. Dec Time [%]	70%
Avg. Geo. Enc Time [%]	103%
Avg. Geo. Dec Time [%]	103%

C2	
Avg. Enc Time [%]	94%
Avg. Dec Time [%]	62%
Avg. Col. Enc Time [%]	113%
Avg. Col. Dec Time [%]	75%
Avg. Ref. Enc Time [%]	99%
Avg. Ref. Dec Time [%]	82%
Avg. Geo. Enc Time [%]	98%
Avg. Geo. Dec Time [%]	102%

CW	
Avg. Enc Time [%]	85%
Avg. Dec Time [%]	51%
Avg. Col. Enc Time [%]	48%
Avg. Col. Dec Time [%]	36%
Avg. Ref. Enc Time [%]	82%
Avg. Ref. Dec Time [%]	67%
Avg. Geo. Enc Time [%]	98%
Avg. Geo. Dec Time [%]	98%

fastRAHT/Haar **encoder-side decoder enabled**, qpChormaOffset = 0, PtsMax = 512 scaleShift = {0, 0, 0}

(a) predgeom predlift vs. fastRAHT and fastHaar, worst case scenario.

C1_ai	lossless geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
Cat3-fused average	-3.8%	-6.7%	-6.5%	1.0%
Cat3-frame average				-3.9%

C2_ai	lossy geometry, lossy attributes [all intra] End-to-End BD-AttrRate [%]			
	Luma	Chroma Cb	Chroma Cr	Reflectance
	-7.0%	-4.3%	-3.8%	-0.2%
				-8.1%

CW_ai	lossless geometry, lossless attributes [all intra] bpip ratio [%]			
	Geometry	Colour	Reflectance	Total
	100.0%	106.6%	106.5%	103.2%
	100.0%		106.1%	101.2%

C1	
Avg. Enc Time [%]	80%
Avg. Dec Time [%]	46%
Avg. Col. Enc Time [%]	27%
Avg. Col. Dec Time [%]	37%
Avg. Ref. Enc Time [%]	39%
Avg. Ref. Dec Time [%]	54%
Avg. Geo. Enc Time [%]	98%
Avg. Geo. Dec Time [%]	97%

C2	
Avg. Enc Time [%]	91%
Avg. Dec Time [%]	60%
Avg. Col. Enc Time [%]	54%
Avg. Col. Dec Time [%]	74%
Avg. Ref. Enc Time [%]	49%
Avg. Ref. Dec Time [%]	79%
Avg. Geo. Enc Time [%]	100%
Avg. Geo. Dec Time [%]	93%

CW	
Avg. Enc Time [%]	80%
Avg. Dec Time [%]	45%
Avg. Col. Enc Time [%]	23%
Avg. Col. Dec Time [%]	26%
Avg. Ref. Enc Time [%]	41%
Avg. Ref. Dec Time [%]	52%
Avg. Geo. Enc Time [%]	99%
Avg. Geo. Dec Time [%]	98%

fastRAHT/Haar **encoder-side decoder disabled**, qpChormaOffset = -1, PtsMax = 512 scaleShift = {4, 4, 4}

(b) predgeom predlift vs. fastRAHT and fastHaar, best case scenario.

Table 8: Comparison of predgeom- predlift vs. fastRAHT and fastHaar.

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Appendices

A. Implementation

The code was implemented on top of TMC13v11.0 commit 2da9f627a9c8311127b9284435c19ce23275e9ff.