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Parallel Implementations of Lambda Domain and R-Lambda Model Rate Control Schemes in a Practical HEVC Encoder

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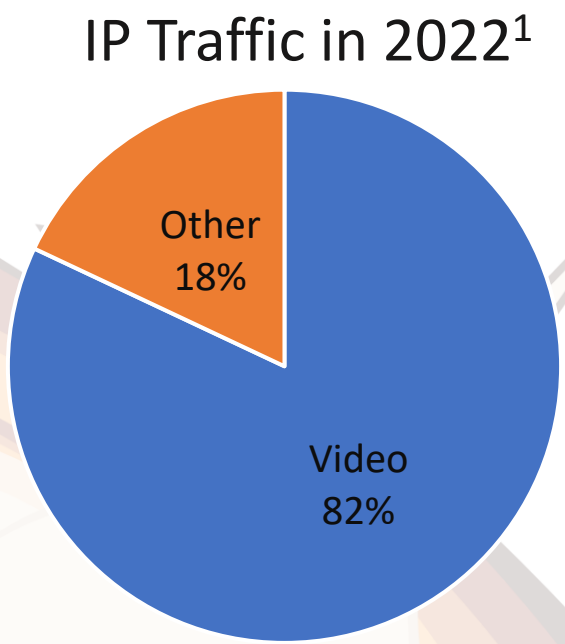
Motivation



- High Efficiency Video Coding (HEVC) was the state-of-the-art during the research
- HEVC reference model (HM)
  - Largely unoptimized
  - Implements all HEVC tools
- Kvazaar
  - Academic open-source encoder
  - Up to 125× the encoding speed of HM at the cost of 2.4% encoding efficiency[2]
- Rate control is needed to deal with bandwidth limitations
- Academically most popular rate control algorithms only implemented in HM

[1]Cisco, Cisco Visual Networking Index: Forecast and Trends 2017-2022, Dec. 2018.

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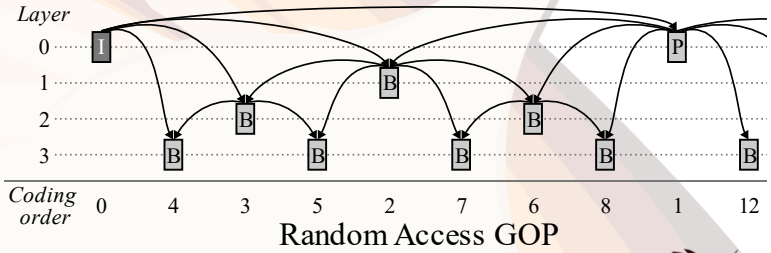
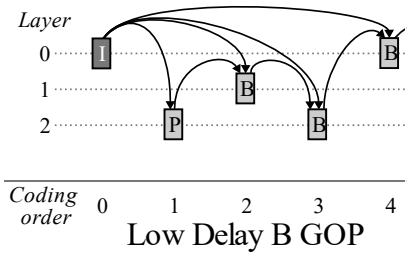
[2]A. Lemmetti, M. Viitanen, A. Mercat, and J. Vanne, "Kvazaar 2.0: fast and efficient open-source HEVC inter encoder," in Proc. ACM Multimedia Syst. Conf., Istanbul, Turkey, June 2020.

HEVC coding structure & rate control

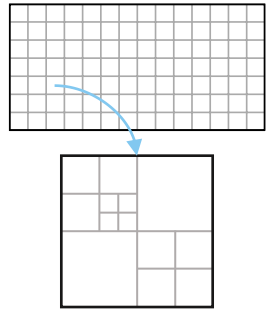
- A sequence is split into Groups of Pictures (GOPs)
- A GOP contains frames that are placed on layer(s)
- Frame is split into Coding Tree Units (CTUs)
- CTUs can be partitioned into Coding Units (CUs)
- A rate control algorithm tries to maximize encoding quality under the bit rate target by distributing bits at different coding structure levels
  - $P_{\text{opt}} = \arg\min_{P}(D + \lambda \times R)$, D is distortion, R is rate



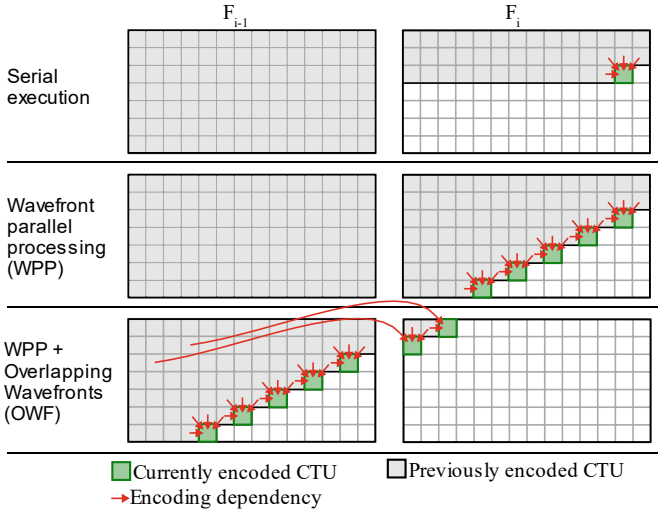
Random Access GOP



Low Delay B GOP



HEVC frame split into CTUs and an example of a CTU split into CUs



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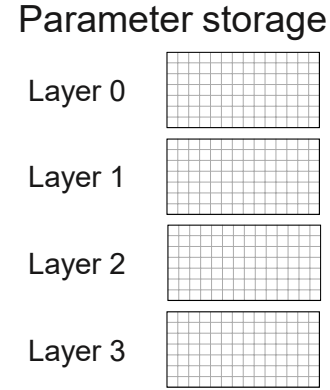
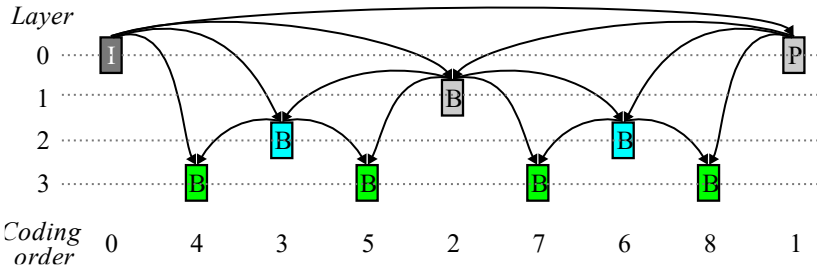
Lambda Domain Rate Control[1]

- Bit allocation at GOP, frame, and CTU level
- $\lambda = \alpha \times R^{\beta}$, α and β are content specific parameters
- Each CTU of a GOP layer shares its α and β values with all frames of said layers.
- The α and β are updated after related CTU is encoded
- With OWF the frames on the lowest level in RA GOP can be encoded fully in parallel
  - ➢Extra synchronization is required





[1]B. Li, H. Li, L. Li, and J. Zhang, "λ domain rate control algorithm for High Efficiency Video Coding," *IEEE Trans. Image Process.*, vol. 23, Sept. 2014, pp. 3841–3854.

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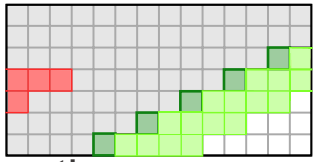
Rate-Lambda Model Rate Control[1]

- GOP and frame level bit allocation and parameter storage structure inherited from the Lambda Domain rate control
- $\lambda = C \times R^{-K-1}$, where C and K are sequence specific parameters
- Initially distribute bits for each CTU of a frame based on the previous frames
- After a CTU is encoded the bits are reallocated for the next 4 CTUs
  - ➢Requires limiting because of WPP
- Combined with OWF the parameter updating interferes with reallocation – the *C* and *K* will have different values for the reallocation than the initial allocation
  - ➢Keep a copy of the original *C* and *K* values
- Still the *C* and *K* values originate from different frames
  - ➢Update parameters after frame is completed, not CTU



[1]S. Li, M. Xu, Z. Wang, and X. Sun, "Optimal bit allocation for CTU level rate control in HEVC," IEEE Trans. Circuits Syst. Video Technol., vol. 27, Nov. 2017, pp. 2409–2424.

Results 1/2

- Lambda Domain is the anchor
- 32 Core Ryzen Threadripper 2990WX
- 16 thread limitation for encoders

Sequential

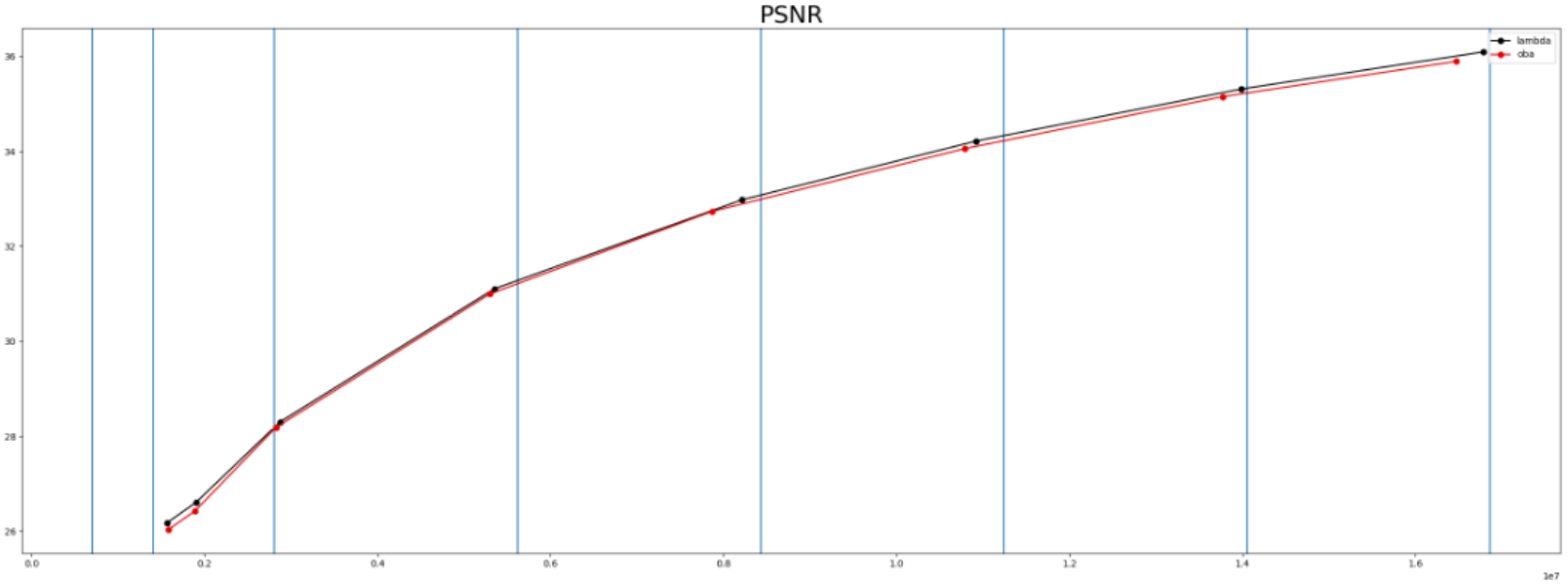
Class	PSNR BDBR	SSIM BDBR	VMAF BDBR	Speedup	R-Lambda Bitrate error	Lambda Bitrate error
Ultrafast RA GOP						
hevc-A	-0.51 %	-5.87 %	1.15 %	0.98×	8.30 %	5.20 %
hevc-B	-0.53 %	-6.67 %	-2.46 %	0.98×	1.09 %	-1.16 %
hevc-C	0.65 %	-1.30 %	1.02 %	0.98×	-0.54 %	-1.61 %
hevc-D	1.87 %	-1.17 %	2.29 %	1.02×	-1.14 %	-1.01 %
hevc-E	-16.26 %	-18.90 %	-18.16 %	1.01×	0.71 %	0.23 %
OVERALL	**-2.35 %**	**-6.21 %**	**-2.85 %**	**0.99×**	**0.97 %**	**-0.29 %**
Ultrafast LB GOP						
hevc-A	-1.19 %	-6.69 %	0.44 %	1.02×	6.39 %	4.55 %
hevc-B	-2.45 %	-8.95 %	-2.99 %	0.99×	0.31 %	-0.33 %
hevc-C	0.22 %	-3.01 %	0.99 %	0.99×	-0.08 %	-0.66 %
hevc-D	0.56 %	-2.90 %	1.60 %	0.98×	-0.05 %	-0.61 %
hevc-E	-9.51 %	-15.14 %	-12.56 %	0.98×	0.16 %	0.56 %
OVERALL	**-2.22 %**	**-7.07 %**	**-2.30 %**	**0.99×**	**0.79 %**	**0.22 %**
Veryslow RA GOP						
hevc-A	-5.18 %	-10.40 %	-2.61 %	1.03×	3.80 %	0.53 %
hevc-B	-5.15 %	-11.14 %	-4.73 %	1.08×	-0.42 %	-1.43 %
hevc-C	-1.18 %	-3.55 %	-0.07 %	1.04×	-1.56 %	-1.74 %
hevc-D	0.09 %	-4.22 %	1.64 %	1.01×	-1.35 %	-1.29 %
hevc-E	-14.53 %	-17.49 %	-15.26 %	1.09×	0.76 %	0.26 %
OVERALL	**-4.67 %**	**-8.89 %**	-3.80 %	**1.05×**	**-0.22 %**	**-0.97 %**
Veryslow LB GOP						
hevc-A	-0.90 %	-2.76 %	0.06 %	1.02×	5.96 %	4.33 %
hevc-B	-1.12 %	-1.68 %	-1.05 %	1.02×	1.01 %	0.70 %
hevc-C	-4.24 %	-7.95 %	-3.86 %	1.03×	0.35 %	0.16 %
hevc-D	-5.77 %	-10.11 %	-3.44 %	1.06×	0.93 %	0.08 %
hevc-E	6.10 %	6.12 %	5.87 %	1.03×	1.28 %	0.85 %
OVERALL	**-1.46 %**	**-3.52 %**	-0.76 %	**1.03×**	**1.51 %**	**0.87 %**

WPP

Class	PSNR BDBR	SSIM BDBR	VMAF BDBR	Speedup	R-Lambda Bitrate error	Lambda Bitrate error
Ultrafast RA GOP						
hevc-A	-0.38 %	-5.71 %	1.35 %	0.92×	9.53 %	5.49 %
hevc-B	-0.48 %	-6.31 %	-2.29 %	0.94×	1.09 %	-1.02 %
hevc-C	0.96 %	-1.01 %	1.35 %	0.97×	-0.39 %	-1.56 %
hevc-D	1.81 %	-1.30 %	2.17 %	0.99×	-1.08 %	-0.96 %
hevc-E	-15.62 %	-18.18 %	-16.97 %	0.97×	0.66 %	0.10 %
OVERALL	**-2.16 %**	**-5.93 %**	**-2.53 %**	**0.96×**	**1.15 %**	**-0.21 %**
Ultrafast LB GOP						
hevc-A	-1.21 %	-6.83 %	0.59 %	0.91×	6.75 %	4.94 %
hevc-B	-2.51 %	-8.93 %	-3.14 %	0.94×	0.34 %	-0.33 %
hevc-C	0.13 %	-3.14 %	0.76 %	0.97×	-0.04 %	-0.62 %
hevc-D	0.74 %	-2.46 %	1.63 %	0.99×	-0.02 %	-0.59 %
hevc-E	-9.95 %	-15.51 %	-13.20 %	0.94×	0.08 %	0.50 %
OVERALL	**-2.30 %**	**-7.07 %**	**-2.48 %**	**0.95×**	**0.84 %**	**0.27 %**
Veryslow RA GOP						
hevc-A	-4.99 %	-9.97 %	-2.55 %	1.02×	3.77 %	0.40 %
hevc-B	-4.55 %	-10.47 %	-4.19 %	1.05×	-0.38 %	-1.42 %
hevc-C	-1.19 %	-3.55 %	-0.07 %	1.03×	-1.51 %	-1.72 %
hevc-D	0.34 %	-3.44 %	2.00 %	1.02×	-1.36 %	-1.29 %
hevc-E	-13.26 %	-15.85 %	-13.24 %	1.05×	0.54 %	0.24 %
OVERALL	**-4.22 %**	**-8.21 %**	**-3.23 %**	**1.03×**	**-0.23 %**	**-0.98 %**
Veryslow LB GOP						
hevc-A	-0.45 %	-2.08 %	0.68 %	1.02×	6.09 %	4.43 %
hevc-B	-1.04 %	-1.55 %	-0.91 %	1.04×	1.15 %	0.73 %
hevc-C	-6.12 %	-9.43 %	-5.24 %	1.02×	0.56 %	0.19 %
hevc-D	-5.68 %	-9.93 %	-3.46 %	1.06×	0.98 %	0.12 %
hevc-E	5.69 %	5.75 %	5.24 %	1.03×	1.31 %	0.93 %
OVERALL	**-2.01 %**	**-4.01 %**	**-1.24 %**	**1.04×**	**1.56 %**	**0.92 %**

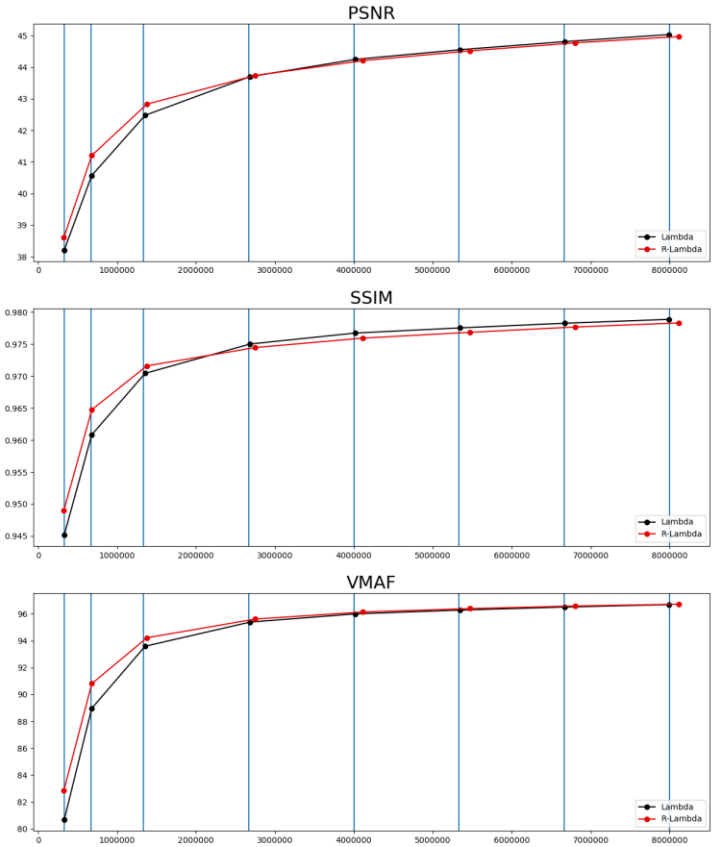
Class A bitrate error

- Blue lines indicate bitrate targets



Class E example

Johnny



Results 2/2

WPP + OWF

Class	PSNR BDBR	SSIM BDBR	VMAF BDBR	Speedup	R-Lambda Bitrate error	Lambda Bitrate error
Ultrafast RA GOP						
hevc-A	-0.13 %	-7.78 %	1.44 %	0.98×	11.93 %	10.43 %
hevc-B	-0.73 %	-6.42 %	-2.64 %	0.95×	1.56 %	-0.60 %
hevc-C	1.43 %	-0.68 %	2.26 %	0.93×	-0.17 %	-1.29 %
hevc-D	1.47 %	-0.99 %	1.63 %	1.01×	-0.82 %	-0.57 %
hevc-E	-14.72 %	-17.42 %	-17.14 %	0.96×	1.25 %	0.58 %
OVERALL	**-2.03 %**	**-5.92 %**	**-2.57 %**	**0.96×**	**1.75 %**	**0.68 %**
Ultrafast LB GOP						
hevc-A	-1.69 %	-6.49 %	0.45 %	0.95×	6.92 %	5.96 %
hevc-B	-3.26 %	-9.02 %	-3.05 %	0.98×	-0.31 %	-1.20 %
hevc-C	-0.59 %	-3.65 %	0.06 %	0.98×	0.58 %	0.09 %
hevc-D	0.64 %	-2.01 %	1.61 %	1.00×	0.57 %	0.18 %
hevc-E	-9.21 %	-14.01 %	-11.18 %	0.96×	-0.21 %	-0.27 %
OVERALL	**-2.62 %**	**-6.82 %**	**-2.24 %**	**0.98×**	**0.90 %**	**0.35 %**
Veryslow RA GOP						
hevc-A	-4.42 %	-10.49 %	-0.96 %	1.04×	8.64 %	5.27 %
hevc-B	-3.98 %	-9.27 %	-3.30 %	1.07×	-0.17 %	-1.11 %
hevc-C	1.88 %	0.75 %	4.32 %	1.01×	-1.14 %	-1.48 %
hevc-D	-0.22 %	-3.37 %	1.37 %	1.01×	-1.26 %	-0.90 %
hevc-E	-12.31 %	-14.45 %	-12.08 %	1.03×	0.96 %	0.66 %
OVERALL	**-3.28 %**	**-6.73 %**	**-1.77 %**	**1.03×**	**0.54 %**	**-0.14 %**
Veryslow LB GOP						
hevc-A	-3.07 %	-6.71 %	-1.21 %	1.04×	6.71 %	5.28 %
hevc-B	-1.08 %	-1.56 %	0.16 %	1.05×	1.31 %	0.54 %
hevc-C	-5.91 %	-9.00 %	-4.58 %	0.95×	1.39 %	0.96 %
hevc-D	-4.41 %	-9.34 %	-1.02 %	1.00×	1.74 %	1.04 %
hevc-E	0.15 %	1.01 %	2.81 %	0.99×	1.58 %	1.34 %
OVERALL	**-2.91 %**	**-5.09 %**	**-0.87 %**	**1.01×**	**2.07 %**	**1.41 %**

Difference between Sequential and WPP + OWF

Class	PSNR BDBR	SSIM BDBR	VMAF BDBR	Speedup	R-Lambda Bitrate error	Lambda Bitrate error
Ultrafast RA GOP						
hevc-A	0.37 %	-1.90 %	0.29 %	0.01×	3.63 %	5.23 %
hevc-B	-0.20 %	0.26 %	-0.18 %	-0.03×	0.48 %	0.56 %
hevc-C	0.78 %	0.61 %	1.24 %	-0.06×	0.37 %	0.33 %
hevc-D	-0.40 %	0.19 %	-0.66 %	-0.01×	0.32 %	0.44 %
hevc-E	1.54 %	1.48 %	1.02 %	-0.05×	0.53 %	0.35 %
OVERALL	**0.33 %**	**0.28 %**	**0.28 %**	**-0.03×**	**0.78 %**	**0.96 %**
Ultrafast LB GOP						
hevc-A	-0.50 %	0.20 %	0.01 %	-0.08×	0.54 %	1.41 %
hevc-B	-0.81 %	-0.08 %	-0.06 %	0.00×	-0.62 %	-0.86 %
hevc-C	-0.82 %	-0.64 %	-0.92 %	-0.01×	0.65 %	0.76 %
hevc-D	0.08 %	0.89 %	0.01 %	0.02×	0.62 %	0.79 %
hevc-E	0.30 %	1.13 %	1.38 %	-0.01×	-0.36 %	-0.83 %
OVERALL	**-0.39 %**	**0.25 %**	**0.06 %**	**-0.01×**	**0.11 %**	**0.12 %**
Veryslow RA GOP						
hevc-A	0.76 %	-0.08 %	1.65 %	0.01×	4.84 %	4.74 %
hevc-B	1.17 %	1.88 %	1.43 %	-0.02×	0.25 %	0.33 %
hevc-C	3.05 %	4.30 %	4.38 %	-0.03×	0.42 %	0.26 %
hevc-D	-0.32 %	0.85 %	-0.26 %	0.00×	0.09 %	0.39 %
hevc-E	2.22 %	3.04 %	3.18 %	-0.06×	0.20 %	0.40 %
OVERALL	**1.39 %**	**2.16 %**	**2.03 %**	**-0.02×**	**0.75 %**	**0.83 %**
Veryslow LB GOP						
hevc-A	-2.18 %	-3.95 %	-1.28 %	0.01×	0.75 %	0.95 %
hevc-B	0.04 %	0.12 %	1.21 %	0.03×	0.30 %	-0.15 %
hevc-C	-1.67 %	-1.05 %	-0.72 %	-0.08×	1.04 %	0.81 %
hevc-D	1.35 %	0.77 %	2.42 %	-0.05×	0.81 %	0.96 %
hevc-E	-5.96 %	-5.11 %	-3.07 %	-0.03×	0.30 %	0.48 %
OVERALL	**-1.45 %**	**-1.57 %**	**-0.11 %**	**-0.02×**	**0.56 %**	**0.54 %**

Conclusion

- Rate-Lambda has better BD-Rate on average
- Lambda Domain has a smaller bitrate error
- Both algorithms are suited for real time encoding
- Viability with Versatile Video Coding should be investigated in the future