Multiple transforms for video coding

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Outline

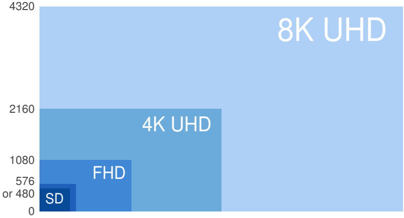
Era of the Internet and videos

Current situation

- In 2014: around 70% of Internet traffic was due to video streaming
- Forecast for 2019: more than 80%[1]

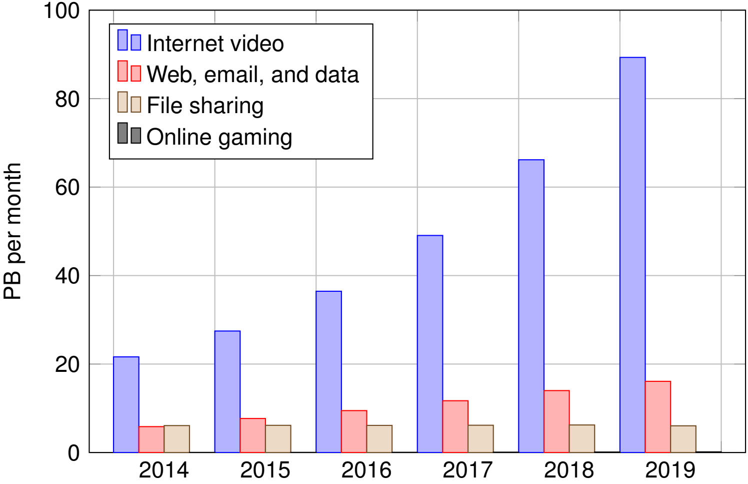
Continuous need for video compression

- **New formats** emerge
- New applications require **improved video quality**
- Need to decrease the bit-rate to stream/store videos



[1] Cisco Visual Networking Index: Forecast and Methodology, 2014–2019 White Paper

Era of the Internet and videos



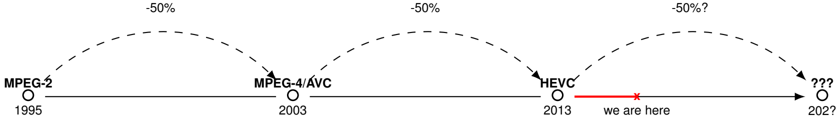
Standardisation

Video coding standards

- The work is inscribed inside a standardisation context
- Latest standard, HEVC, was released in 2013

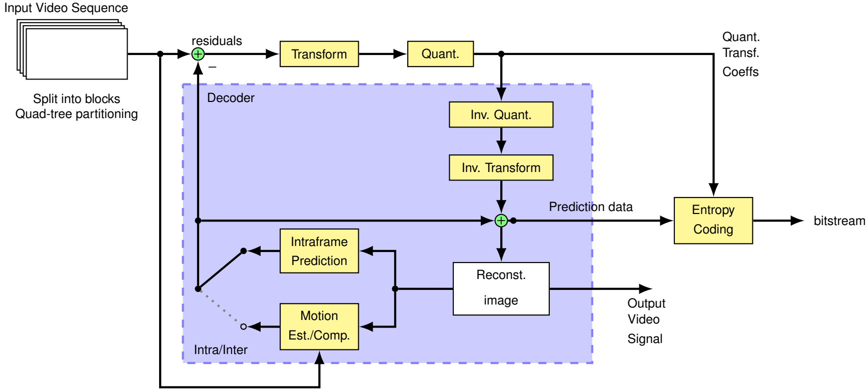
Working context

- Beginning of the standardisation phase
- Exploratory phase with relaxed complexity constraints
- Goal: achieve a suitable solution for a video coding standard for around 2020.



The hybrid video coding scheme

Used in most video coding standards



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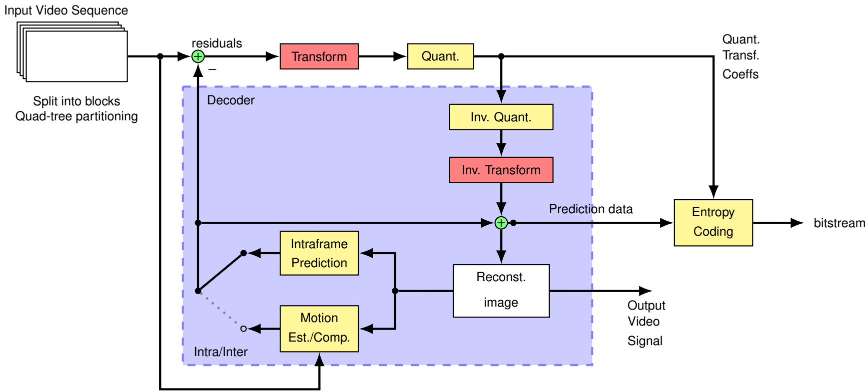


Outline

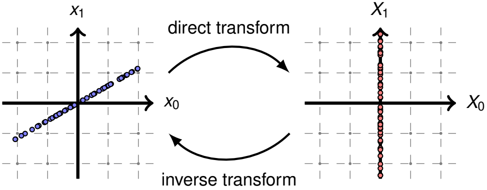
Introduction to transforms

Definition

- A transform is a mathematical function of a signal from a representation domain to another, e.g. a rotation (2D)
- A transform is a change of basis

Desirable properties

- Low complexity
  - real time
  - battery drain
- Compact representation
- Orthogonality
  - perfect reconstruction
  - easily invertible



Separability and non-separability

Pros & Cons

Non-separable

- Able to exploit any linear correlation within a block
- They require $\approx N^4$ operations

Separable

- Able to decorrelate pixels sharing rows or columns
- They require $\approx 2N^3$ operations

0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Example with $N = 4$

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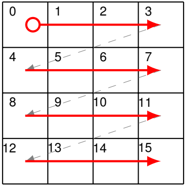

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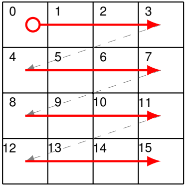
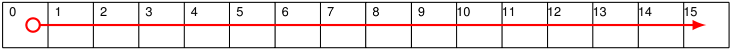


Example with $N = 4$



What kind of data is processed by transforms?

Particular case of HEVC

Residual blocks

- Difference between:
  - original block
  - predicted block
- Examples:

- The same transform is used for all of them

They are generated as different combinations of

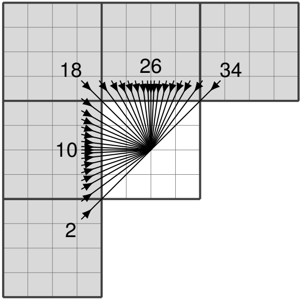
- transform units (TUs): 32, 16, 8, 4
- predictions
  - spatial or intra: 0,1,. . . ,34
  - temporal or inter

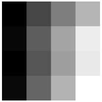
The choice is made by the encoder

- it selects the best combination in terms of:
  - distortion
  - rate

The intra prediction scheme

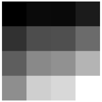
Intra Prediction Modes (IPMs)





Average residual for IPM 10

Average residual for IPM 18



Average residual for IPM 26

How are transforms conceived?

The trade-off

$J(\lambda) = \text{Distortion} + \lambda \text{ Rate}$

State of the art

- KLT → Optimal transform assuming
  - large amount of bits → High-resolution quantisation hypothesis
- Hypothesis for optimality is not valid in video coding
- RDOT → Alternative design approach[1]
  - focused on signal sparsity in the transform domain

References

[1] O.G. Sezer — Sparse orthonormal transforms for image compression, 2008

The rate-distortion optimised transform

RDOT design features

- Minimise the distortion and the number of significant coefficients
- Use a simple model for the bit-rate
  - ℓ_0 norm: number of non-zero coefficients
- Sparsity suits video coding syntax elements

The RDOT equation

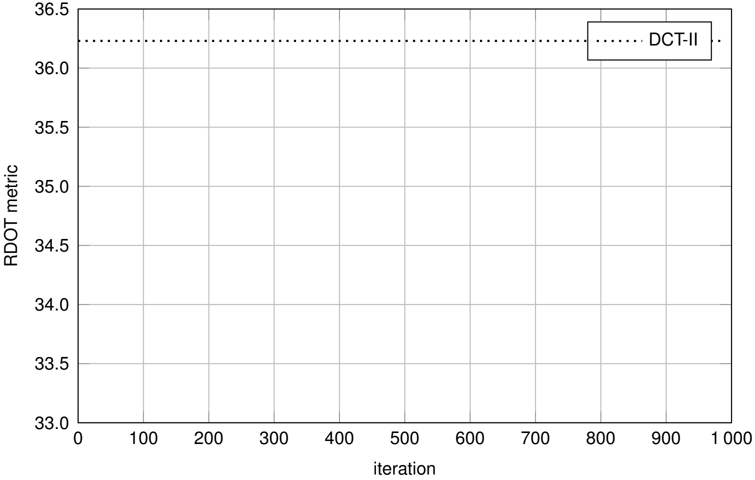
$$J(\lambda) = \sum_{\forall i} \underbrace{\left\| \mathbf{x}_i - \mathbf{A}^T \cdot \mathbf{c}_i \right\|^2}_{\text{Distortion}} + \lambda \underbrace{\left\| \mathbf{c}_i \right\|_0}_{\text{rate}} \quad \text{with} \begin{cases} \mathbf{x}_i & \text{residuals} \\ \mathbf{A} & \text{transform} \\ \mathbf{c}_i & \text{transf. \& quant. coeff.} \\ \lambda & \text{Lagrange multiplier (PDF independent)} \end{cases}$$

- iterative algorithm

Objective

- For a given set of residuals $\mathbf{x}_i$'s
- Find the transform $\mathbf{A}$ that minimises $J(\lambda)$

RDOT metric for different transforms on 4×4 residuals



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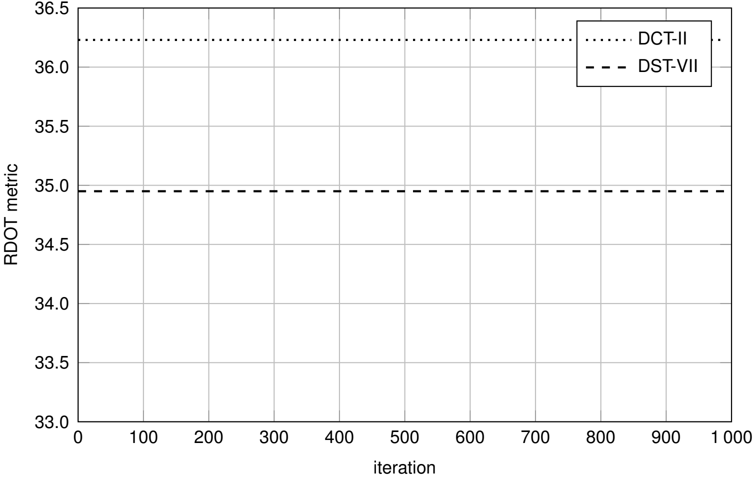

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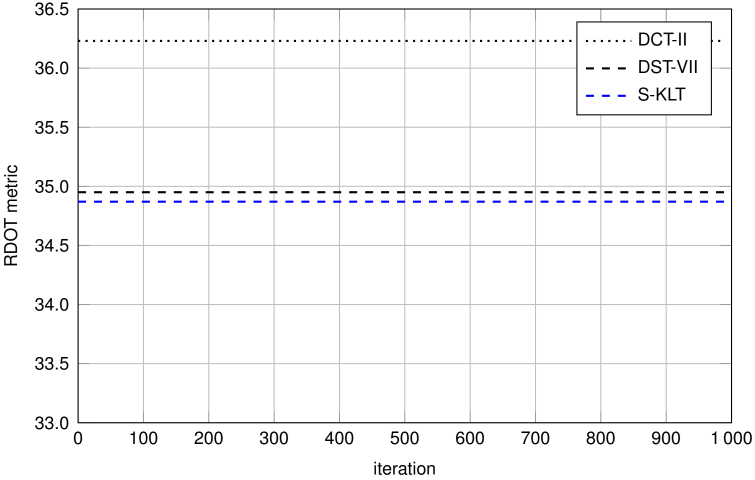

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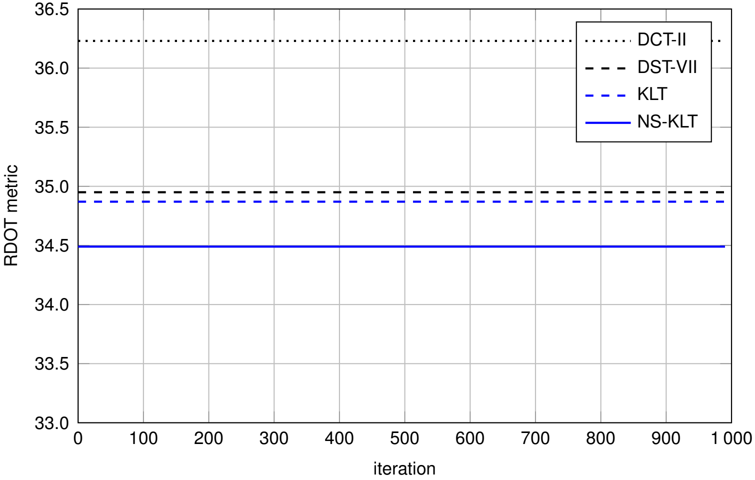

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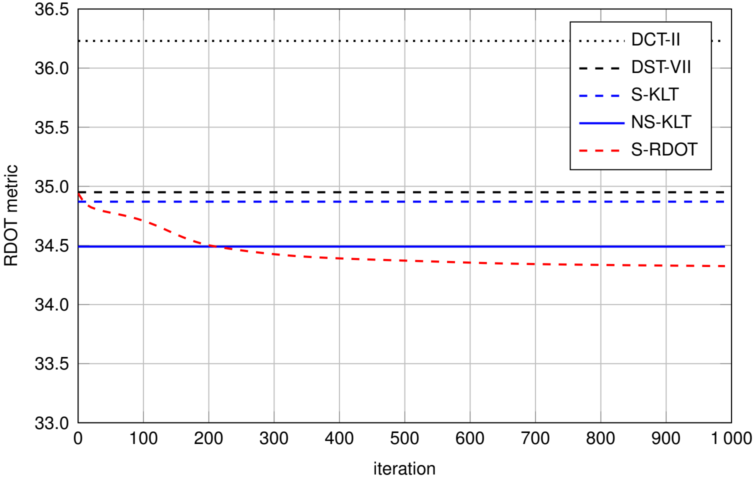

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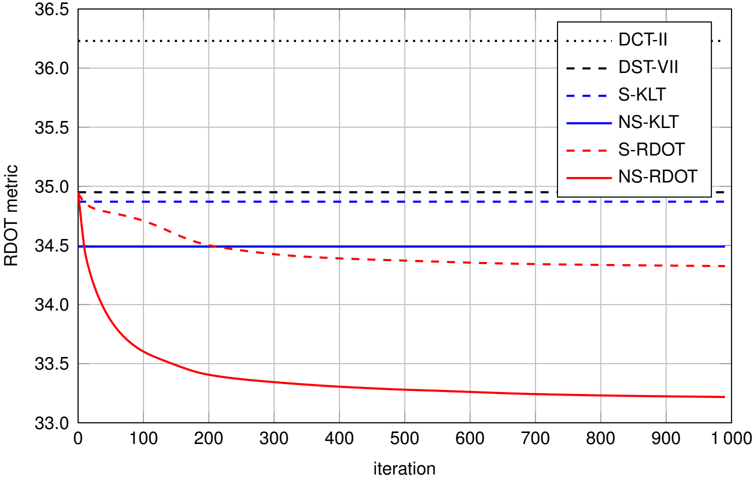


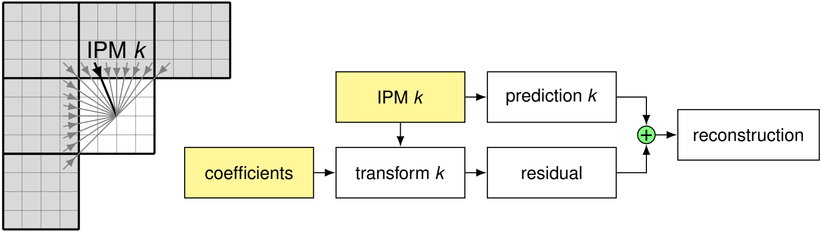
Experiment: Using the transforms in HEVC

Mode-dependent directional transforms (MDDT) for 4 × 4 and 8 × 8 TUs

Learning phase

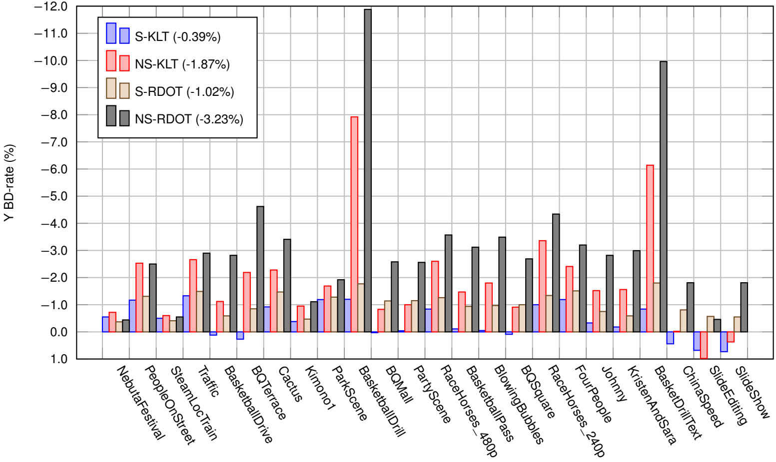
- Learn an adapted transform to each of the 35 IPMs (MDDT)
- Replace the default HEVC transforms (no additional signalling) with:
  - KLT
  - RDOT

Decoding scheme



MDDT performances on the HEVC test set

Y BD-rate (%) on AI for 4×4 and 8×8 blocks



Conclusions

Performance over HEVC

	KLT		RDOT	
	sep	non-sep	sep	non-sep
Y BD-rate	-0.39%	-1.87%	-1.02%	-3.23%
Encoding	108%	112%	108%	112%
Decoding	105%	120%	105%	120%
ROM	8.20 kB	148.75 kB	8.20 kB	148.75 kB

Transform design

- RDOT design provides significant better results than the KLT design
- Separability plays an important role on the performance
  - complexity (encoding/decoding)
  - storage requirements
  - bit-rate savings

Next steps

- Find out the limits of this technique

Outline

Mode-dependent transform competition (MDTC)

Motivations

- Residual variability even inside the same IPM
- Significantly better results using RDOTs in MDDT than KLTs

Multiple transform design for HEVC

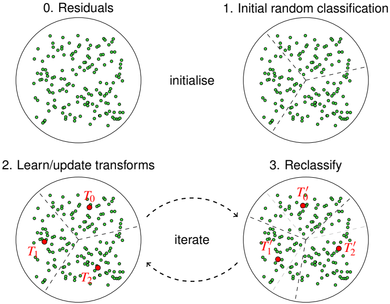
- Conservative approach → $1 + 2^N$ transforms
  - default transform (DCT/DST) + additional RDOTs
  - signalling → flag plus fixed length codeword
- Learning algorithm → based on the RDOT metric

Multiple transform design

Classic clustering method: classify/update

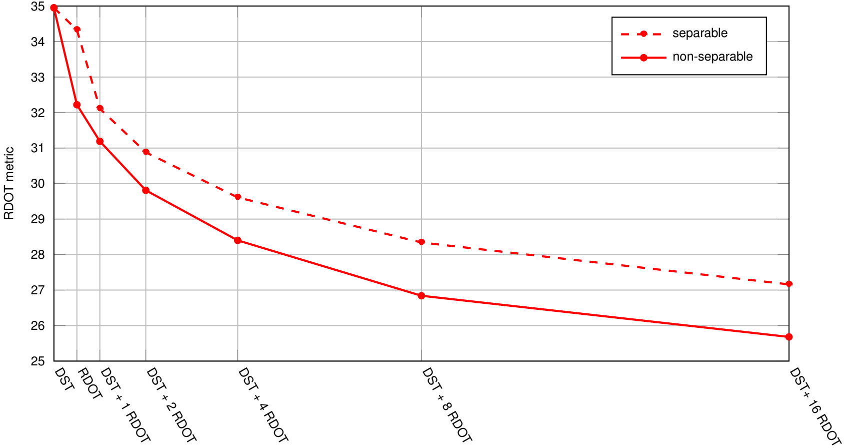
Using the RDOT metric

- $J(\lambda) = \sum_{\forall i} \left\| \mathbf{x}_i - \mathbf{A}^T \cdot \mathbf{c}_i \right\|^2 + \lambda \left\| \mathbf{c}_i \right\|_0$
- It is used to evaluate a transform
  - compute the optimal transform for a set of residuals
  - assign each residual to the transform that minimises $J(\lambda)$
- It allows creating an iterative clustering algorithm



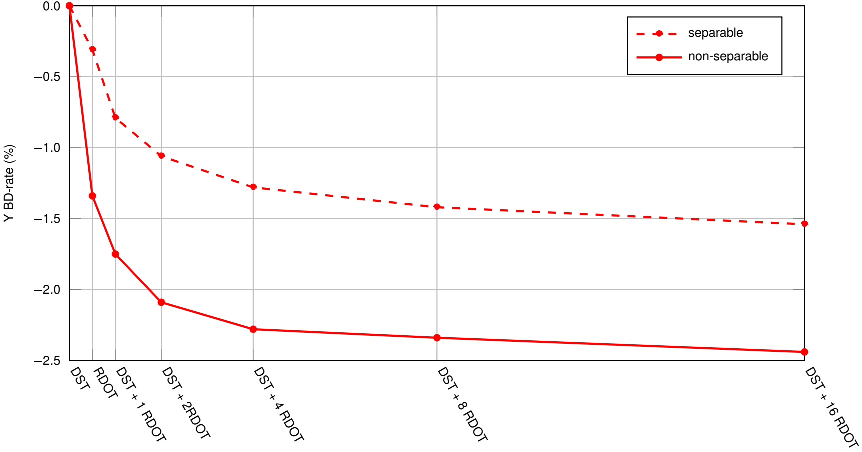
Learning results

Averaged RDOT metric for 4 × 4 blocks across all IPMs



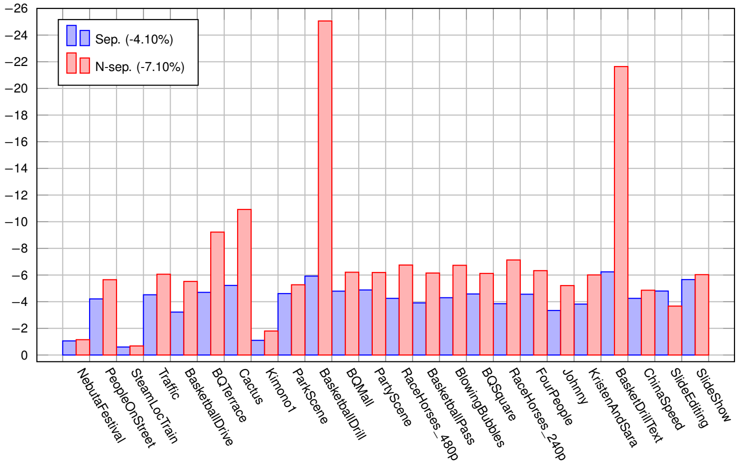
Results in video coding on top of HEVC

Y BD-rate (%) for 4×4 blocks



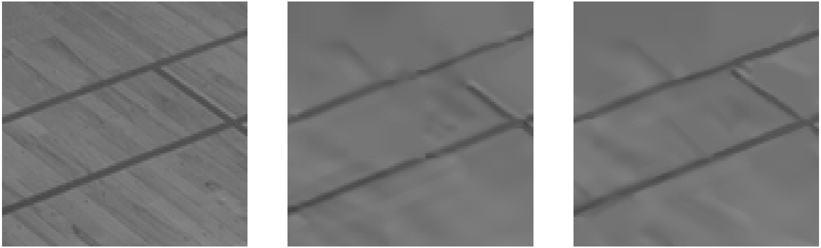
MDTC performances in detail

Y BD-rate (%) for High Performance System: $4 \times 4 : 1 + 16$ & $8 \times 8 : 1 + 32$



MDTC performances in detail

Graphical improvement at QP 37 on BasketballDrill (3 Mbps)



(a) Original (b) HEVC (c) MDTC

Figure: Comparison between HEVC and MDTC

Conclusions

Performances

	4×4: 1+16	8×8: 1+32
	sep.	non-sep.
Y BD-rate	-4.10%	-7.10%
Enc. Time	800%	2000%
Dec. Time	105%	120%
ROM	236.25 kB	4.51 MB

Next steps

- Important bit-rate savings thanks to transform competition
- Non-separable transforms are very complex
  - encoding/decoding complexity
  - storage requirements
- Simplify MDTC systems to make them usable

Outline

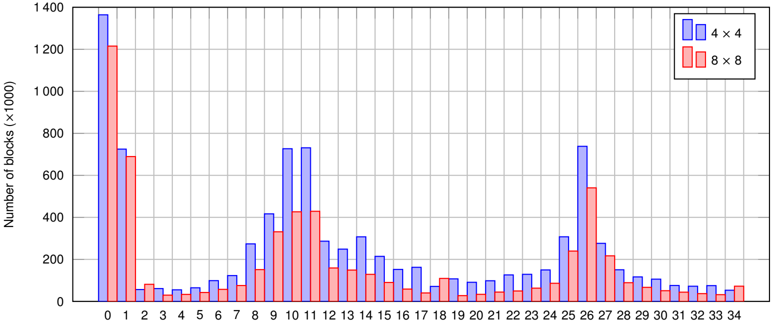
Outline

1. General introduction
2. Transform coding
3. Mode-dependent transform competition
4. Simplifications of the MDTC systems
   - ROM limitations on MDTC systems
   - MDTC systems based on Discrete Trigonometric Transforms
5. Conclusions

Different number of transforms per IPM

Observations

- Proposed MDTC uses the same number of transforms in all IPMs
- IPM usage is not uniform: there are some favoured modes (MPM)

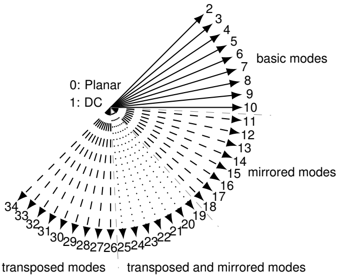


Symmetries in intra prediction residuals

Observations

- Residuals coming from specific IPMs present geometrical relations
- With proper manipulation, transforms can be reused

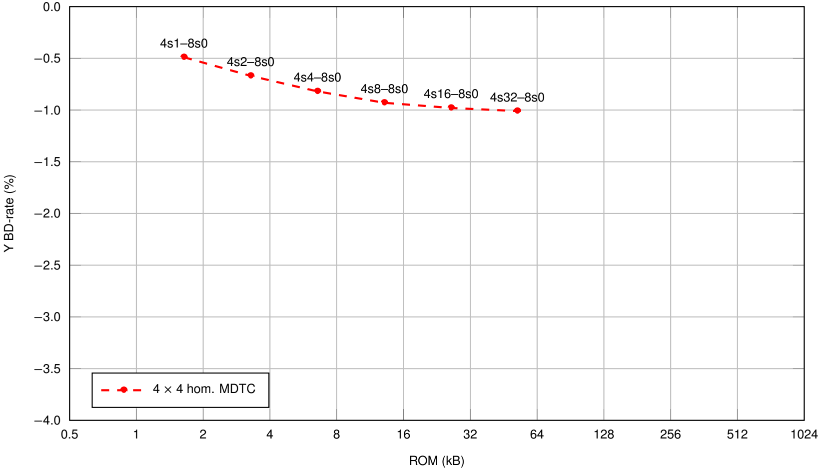
Graphical interpretation



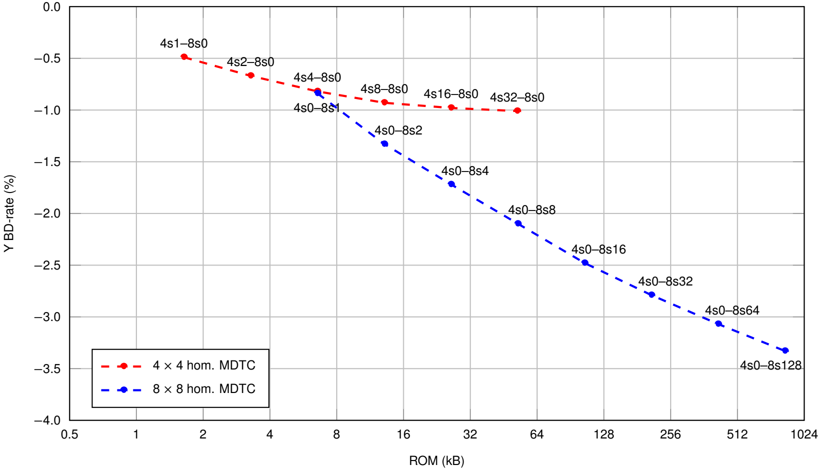
Operations applied to blocks

$$\mathbf{X} = \begin{cases} \mathbf{A}\,\mathbf{x} & 0 \leq \text{IPM} \leq 10 \\ \mathbf{A} \circlearrowleft \mathbf{x} & 11 \leq \text{IPM} \leq 18 \\ \mathbf{A} \circlearrowleft \mathbf{x}^T & 19 \leq \text{IPM} \leq 25 \\ \mathbf{A}\,\mathbf{x}^T & 26 \leq \text{IPM} \leq 34 \end{cases}$$

Results on the ROM — BD-rate plane



Results on the ROM — BD-rate plane



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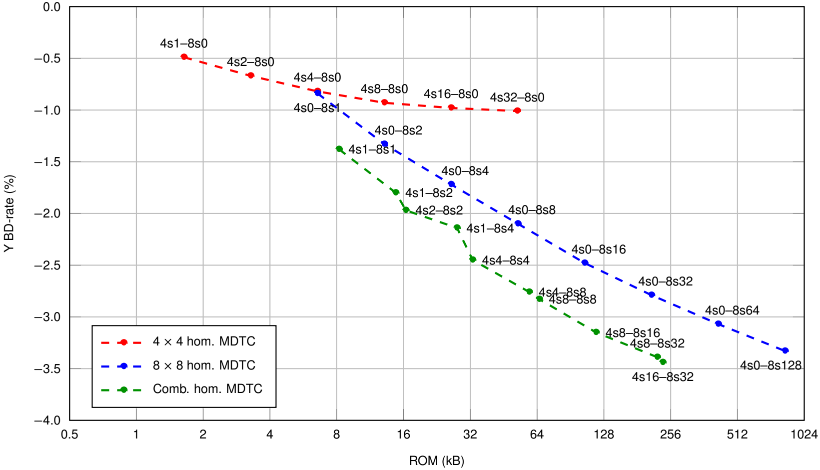

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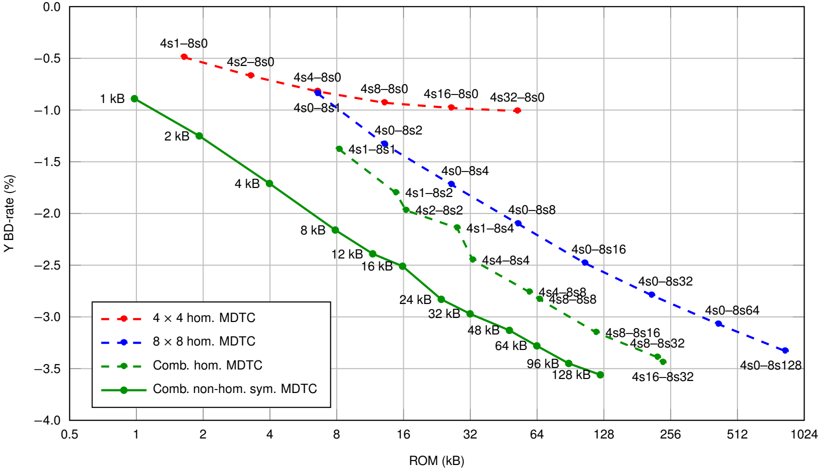


Summary and conclusions

Systems on demand (performances on the HEVC test set)

System	16 kB	32 kB	64 kB	128 kB
Y BD-rate	-2.87%	-3.21%	-3.55%	-3.79%
Encoding	372%	481%	761%	1297%
Decoding	105%	105%	105%	105%

Remarkable points

- ROM can be reduced up to a third of its original value
- Bit-rate savings are maintained
- Coding complexity remains more or less untouched

Outline

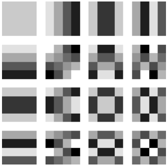
Discrete Trigonometric Transforms (DTTs)

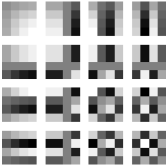
DCTs and DSTs

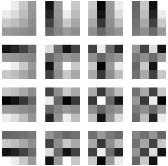
DTT strengths

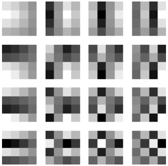
- Fast algorithms
  - number of operations in the order of $N \log_2 N$ instead of N^2
- Transform coefficients can be computed analytically
  - notable reduction in storage requirements
- They can be more easily pushed into a standard

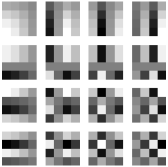
Examples of 4×4 DTTs

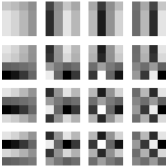

(a) **DCT-II — DCT-II**

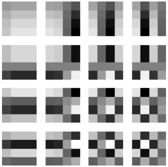

(b) **DST-VII — DST-VII**

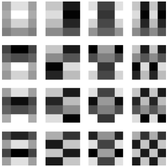

(c) DCT-IV — DCT-IV


(d) DCT-III — DCT-IV


(e) DST-VII — DCT-IV


(f) DST-V — DCT-IV


(g) DST-VII — DCT-V


(h) DST-VII — DST-II

Designing a DTT-based MDTC system

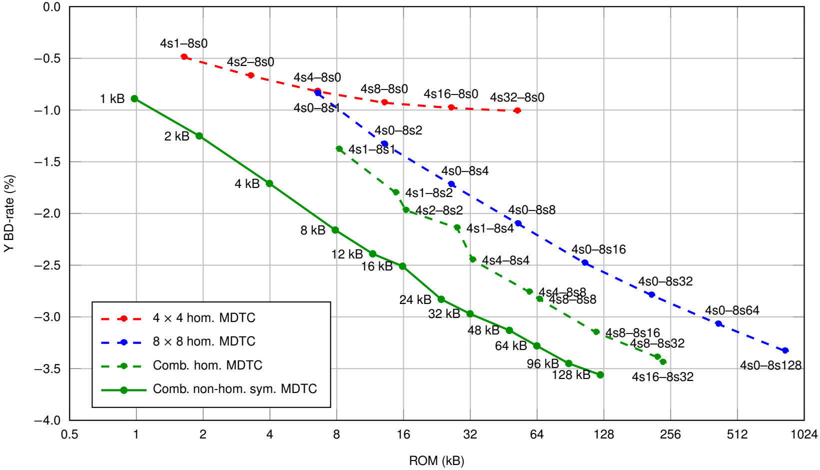
Using the RDOT metric to classify

- Transforms are already known (8 DCTs, 8 DSTs and their inverses)
- There are 256 possible transforms
- Complexity of the classifying algorithm:
  - selection the best combination of N transforms amongst 256
  - example for $N = 4$:

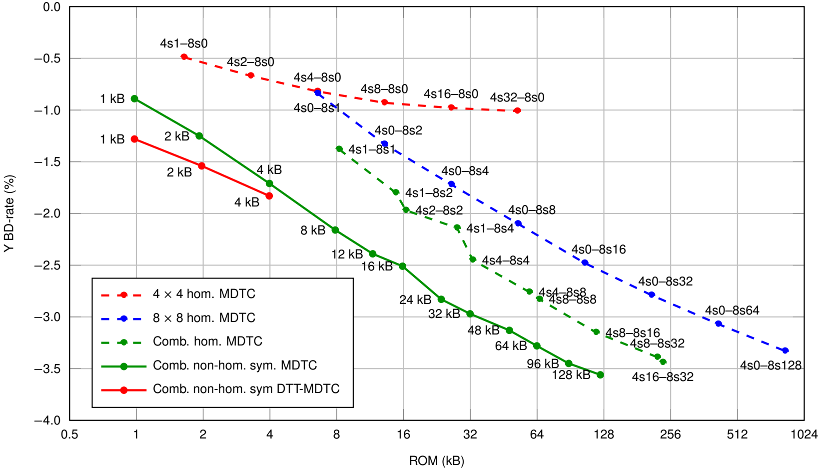
$$\binom{256}{4} = 174\,792\,640 \approx 1.75 \times 10^{8} \tag{1}$$

- The algorithm suboptimality increases with N
- Symmetries and non-homogeneous repartition of transforms are used with DTTs

Performances of DTT-based MDTC systems



Performances of DTT-based MDTC systems



Summary

DTT-based MDTC system compared to RDOT-based ones

	DTT			RDOT		
System	1 kB	2 kB	4 kB	1 kB	2 kB	4 kB
Y BD-rate	-1.28%	-1.54%	-1.86%	-0.89%	-1.25%	-1.71%
Encoding	164%	177%	230%	126%	150%	175%
Decoding	100%	100%	100%	105%	105%	105%

Remarkable points

- Almost 2% bit-rate savings with low complexity
- Performances could be higher by improving the learning algorithm
- DTTs make transforms for bigger block sizes more reasonable
  - room for improvement when using 16×16 or even 32×32 transforms

Outline

Conclusions

Interest of multiple transforms for video coding

- This technique alone is able to achieve significant bit-rate savings over HEVC, depending on complexity:
  - non-separable transforms: up to 7%
  - separable transforms: up to 4%
  - DTTs: 2% (in progress)
  - reminder: HEVC improves intra coding by 22% over AVC
- Systematic on demand design with the RDOT metric
  - the ℓ_0 has proved to be a robust rate approximation
  - independence from residuals PDF has been proved

Perspectives and future work

Immediate action points

- extend the system
  - bigger TU sizes
  - inter coding (gain in RA is about 2/3 of AI)
  - chroma
- coding complexity
  - incomplete transforms
  - exhaustive search might not be necessary
- transform signalling and quantisation

Multiple transforms in future video formats

- Multiple transforms are part of the preliminary draft for a future video coder by ITU and MPEG

Publications

Conference papers

- 2 VCIP 2014 presented papers
- 2 ICIP 2015 presented papers
- 1 ICASSP 2016 submitted paper

Patents

- 5 filled patent applications

Thank you for your attention

Questions?

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