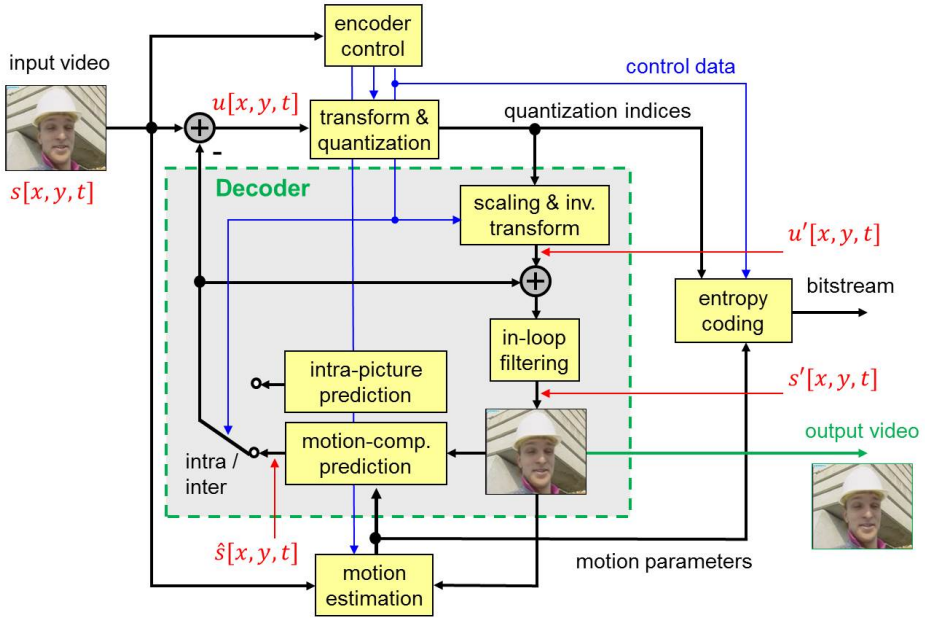
Source Coding and Compression

Heiko Schwarz



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PartII:

Application in Image and Video Coding

Outline

Part I: Source Coding Fundamentals

- Probability, Random Variables and Random Processes
- Lossless Source Coding
- Rate-Distortion Theory
- Quantization
- Predictive Coding
- Transform Coding

Part II: Application in Image and Video Coding

- **Still Image Coding / Intra-Picture Coding**
  - Representation of Images and Video
  - JPEG
  - Intra-Picture Coding in MPEG-2 Video
  - Intra-Picture Coding in H.263 and MPEG-2 Visual
  - Intra-Picture Coding in H.264/AVC
  - Intra-Picture Coding in H.265/HEVC
- Hybrid Video Coding (From MPEG-2 Video to H.265/HEVC)

Still Image Coding / Intra-Picture Coding – Overview

Still Image Coding

- Exchange, transmission and storage of images
- Used in virtually all digital cameras and picture editing applications
- JPEG: Most widely used image compression standard (based on DCT)
- JPEG-2000: Wavelet-based image compression (not discussed in lecture)
- JPEG-XR: Several improvements over JPEG (not discussed in lecture)

Intra-Picture Coding for Video

- Intra-picture coding: Some pictures of a video sequence need to be coded without referring to other picture inside the video sequence
- First picture of a video sequence has to be intra-picture coded
- Intra pictures in regular intervals (e.g., 1s) are required for enabling random access
- Typically, regularly inserted intra pictures consume large amount of bit rate
- H.262 | MPEG-2 Video / H.263 / MPEG-4 Visual: Conceptually similar to JPEG
- H.264 | MPEG-4 AVC: Additional coding tools yielding improved coding efficiency
- H.265 | MPEG-H HEVC: Increased flexibility and improved coding efficiency

Representation of Images and Video

Digital Images and Video

Image

- 2-d function $s(x, y)$ relating light intensity s to spatial coordinates (x, y)

Digital image

- Representation of a continuous image at discrete coordinates $[x, y]$
- Amplitudes $s[x, y]$ have finite alphabet, typically determined by the used bit depth
- Digital gray-level image of size $M \times N$ can be represented using a matrix notation

$$\begin{bmatrix} s[0,0] & s[1,0] & \cdots & s[M-1,0] \\ s[0,1] & s[1,1] & \cdots & s[M-1,1] \\ \vdots & \vdots & \ddots & \vdots \\ s[0,N-1] & s[1,N-1] & \cdots & s[M-1,N-1] \end{bmatrix}$$

- Typically characterized by image size $M \times N$ and bit depth
- Color images are typically composed of 3 sample arrays (for different color components)

Digital video

- Sequence of digital images captured at successive time instances
- Typically characterized by frame rate (in addition to image size and bit depth)

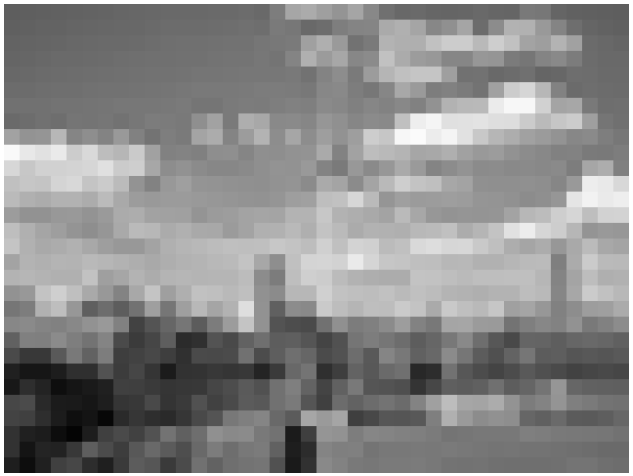
Spatial Resolution

Number of samples ($M \times N$) for discrete matrix representation

320×240 samples

160×120 samples

80×60 samples



40×30 samples

Gray-Level Resolution / Bit Depth

Number of gray levels for image representation (typically determined by bit depth)

256 gray levels (8 bit)

64 gray levels (6 bit)

16 gray levels (4 bit)

4 gray levels (2 bit)

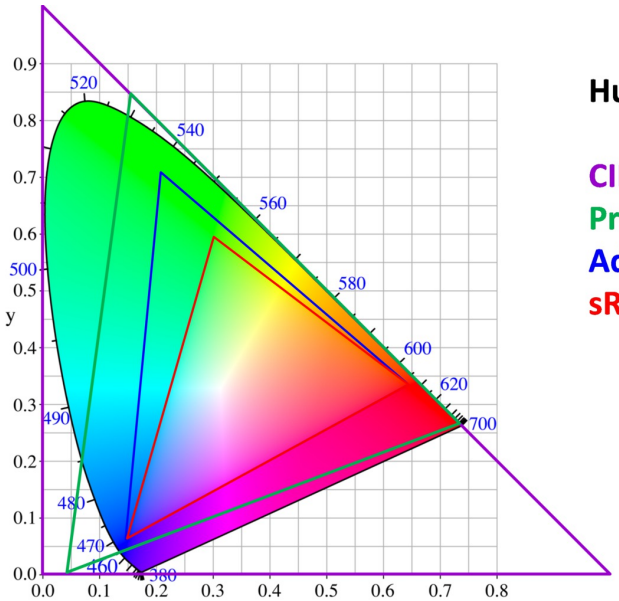
Representation of Color Images

Color components

- Require at least 3 color components (trichromatic vision)
- RGB typically used as reference color space
- Need to specify color of RGB primaries in CIE XYZ reference space

BT.709 RGB parameters

primary	x	y
red	0.6400	0.3300
green	0.3000	0.6000
blue	0.1500	0.0600
white D65	0.3127	0.3290



YCbCr Color Space

Definition of YCbCr color space

- More correct name is Y'CbCr, since Y' is a gamma-adjusted luminance component
- Not an absolute color space, but a different representation for RGB data
- Transform of gamma-adjusted and normalized RGB components r', g' and b' with a range of 0..1
- Typically used transform for 8-bit components Y, Cb and Cr

$$\begin{aligned} Y' &= \mathrm{Round}(219 \cdot y' + 16) \\ Cb &= \mathrm{Round}(224 \cdot pb' + 128) \\ Cr &= \mathrm{Round}(224 \cdot pr' + 128) \end{aligned}$$

with

$$\begin{aligned} y' &= K_R \cdot r' + (1 - K_R - K_B) \cdot g' + K_B \cdot b' \\ pb' &= 0.5 \cdot (b' - y')/(1 - K_B) \\ pr' &= 0.5 \cdot (r' - y')/(1 - K_R) \end{aligned}$$

- The coefficients K_R and K_B are specified by application standards
- ITU-R Rec. BT.709 specifies $K_R = 0.2126$ and $K_B = 0.0722$
- Y' is called **luma** component, Cb and Cr are called **chroma** components

Advantages of YCbCr Color Representation

Properties of the YCbCr color representation

- Similar color decorrelation as in human visual system:
  - Y' component is related to brightness
  - Cb component represents a yellow-blue difference signal
  - Cr component represents a red-green difference signal
- Coding errors are introduced in perceptual meaningful way
- Effectiveness for coding of images and video experimentally verified

color image

Y' component

Cb component

Cr component

Subsampling of Chroma Components

Y channel

Cb channel

Cr channel

Visual importance of luma and chroma components

- YCbCr color space roughly approximates the color decorrelation in the human visual system
- Human visual system is more sensitive to details in luma (brightness) channel than to details in chroma channels
- Chroma channels can be downsampled for saving bit rate
- Chroma downsampling by a factor of 2 in horizontal or both spatial directions
- Location of chroma samples relative to luma samples has to be specified

Demonstration of Luma/Chroma Perception

Compare luma and chroma perception

- Selective low-pass filtering for luma or chroma components
- Use low-pass filter (1,4,6,4,1)/16

Order of presentation

1. Original luma and chroma components
2. Low-pass filtered luma component but original chroma components
3. Original luma and chroma components (repeated)
4. Original luma component but low-pass filtered chroma components

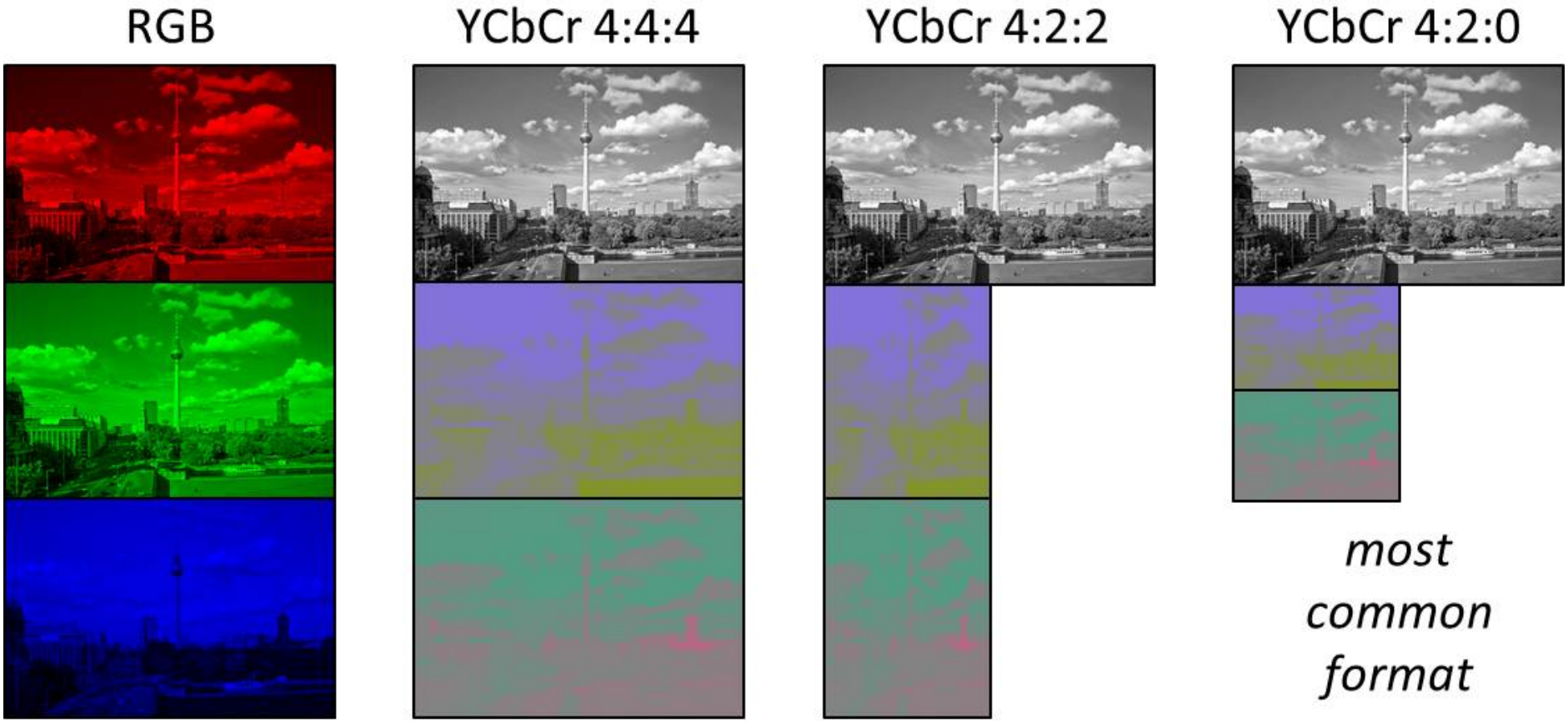
Demonstration: Original Picture

Demonstration: Filtered Luma Component

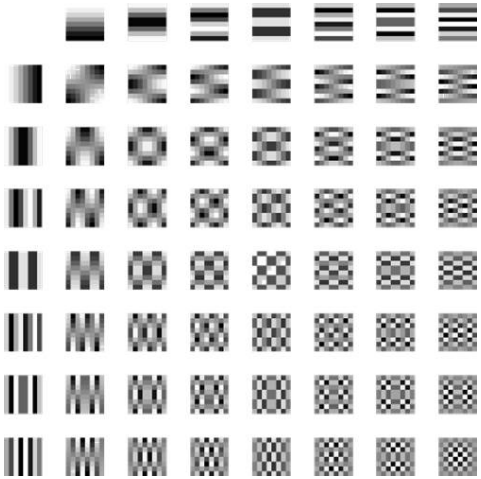
Demonstration: Original Picture (Repeated)

Demonstration: Filtered Chroma Components

Chroma Sampling Formats for Image and Video Coding



JPEG



JPEG – Overview

Joint Photographic Experts Group (JPEG)

- Standard is named after the group which created it
- Joint committee between ITU-T (formerly CCITT) and ISO/IEC JTC 1

Standard "*Digital Compression and Coding of Continuous-Tone Still Images*"

- Officially ITU-T Rec. T.81 and ISO/IEC 10918-1
- Commonly referred to as *JPEG*
- Specifies compression for gray-level and color images
- Work commenced in 1986, standard published in 1992

Applications of JPEG

- Storage format used in virtually all digital cameras (except for "raw" sensor data)
- Most pictures in the Internet are JPEG pictures
- Motion-JPEG is de facto standard for digital video editing

The Scope of Image and Video Coding Standardization

What is standardized?

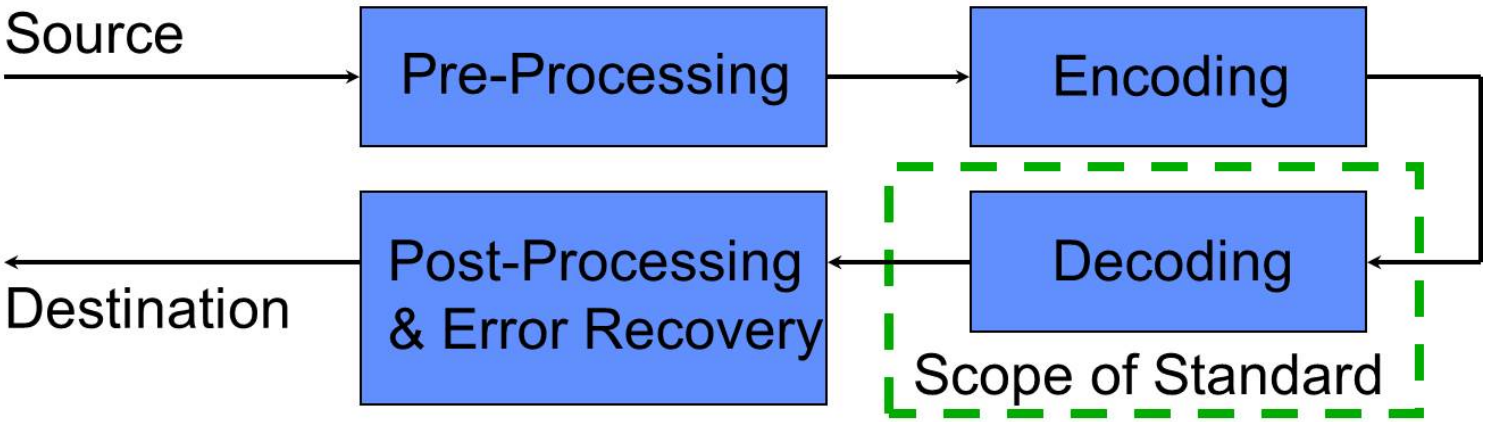
- **Data format** including constraints for the data
- **Decoding result** to be produced by a conforming decoder

⇒ Provides interoperability between different devices

⇒ Permits optimization beyond the obvious

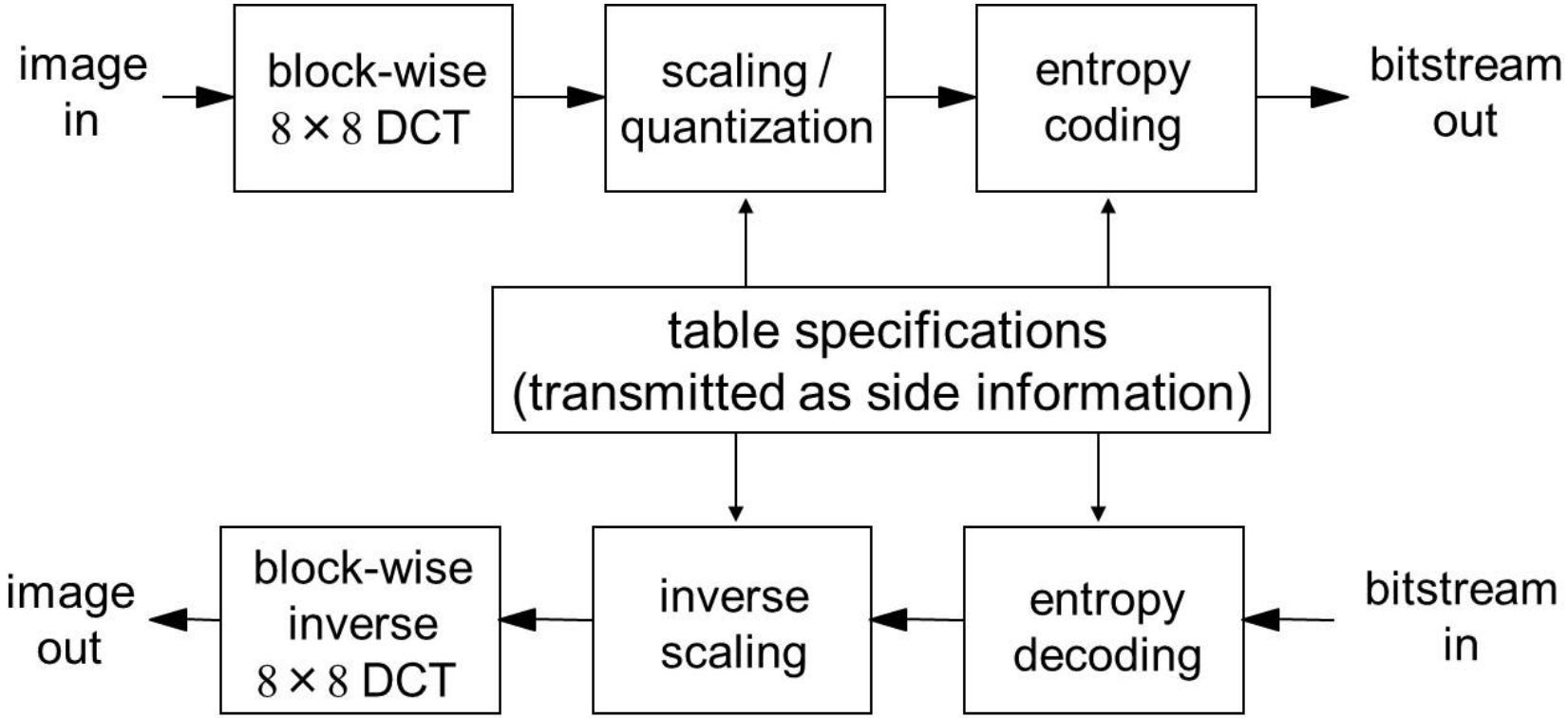
⇒ Permits complexity reduction for implementability

⇒ Provides no guarantee of quality



JPEG: Basic Codec Structure

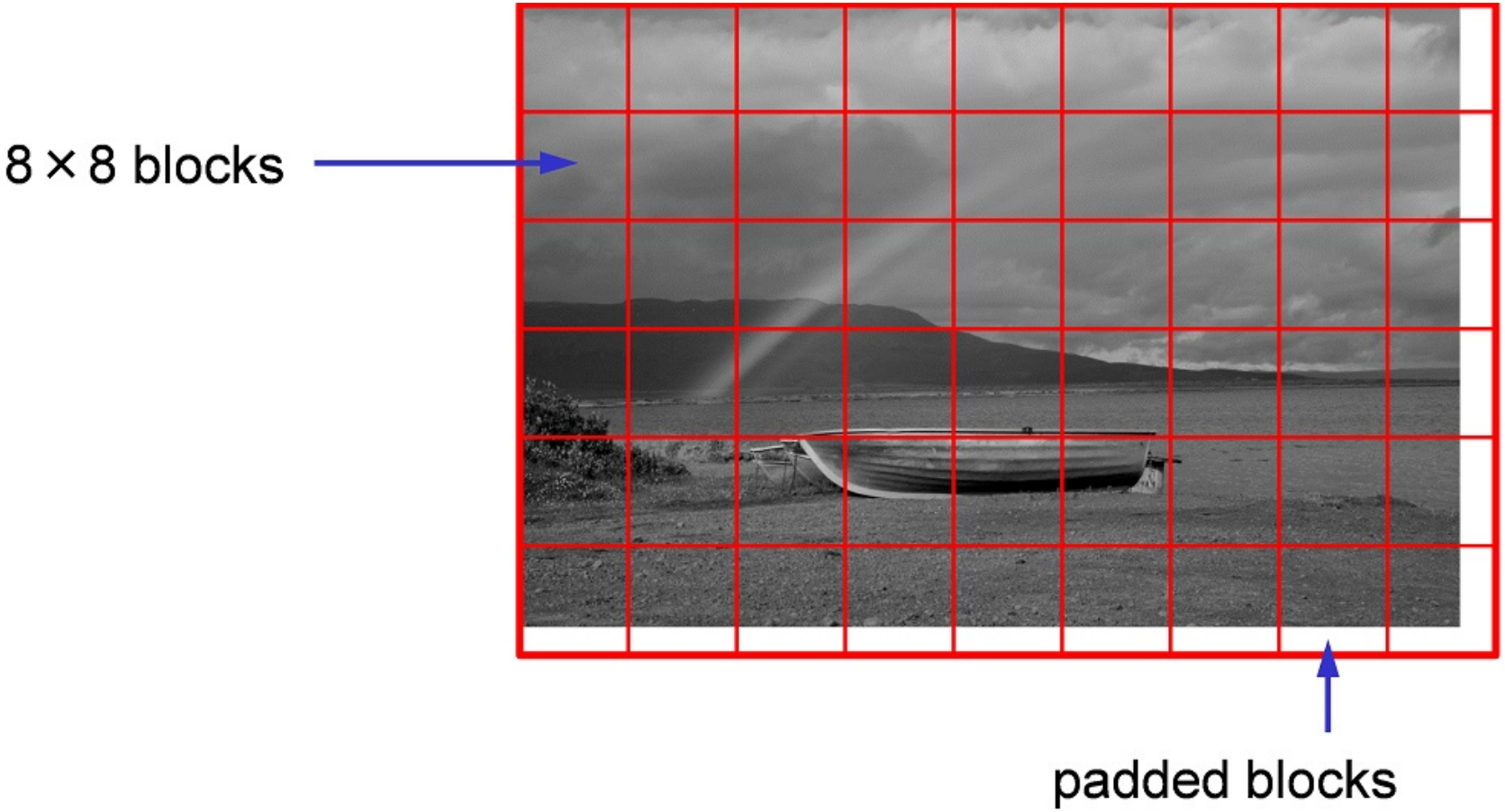
Encoder and decoder structure for each color component



JPEG: Partitioning of Color Components into 8×8 Blocks

Color components are coded independently of each other

- Color components are partitioned into 8×8 blocks (padding at borders)
- The 8×8 blocks are coded using transform coding



Two-dimensional Transform for Image Compression

Separable and symmetric 2-d orthogonal block transform

- 2-d linear transform: Each input block is represented as a linear combination of 2-d basis functions (or basis blocks)
- Separable and symmetric 2-d orthogonal block transform:
  Transform of an $N \times N$ block $\boldsymbol{s}$ can be written as

$$\boldsymbol{u} = \boldsymbol{A} \cdot \boldsymbol{s} \cdot \boldsymbol{A}^{\mathrm{T}} \tag{588}$$

  where $\boldsymbol{A}$ is the $N \times N$ transform matrix and $\boldsymbol{u}$ is the $N \times N$ block of transform coefficients
- Inverse of separable and symmetric 2-d orthogonal block transform is given by

$$\boldsymbol{s}' = \boldsymbol{A}^{\mathrm{T}} \cdot \boldsymbol{u}' \cdot \boldsymbol{A} \tag{589}$$

- Great practical importance:
  Separable transform requires 2 matrix multiplications of size $N \times N$ instead of one multiplication of a vector of size $1 \times N^2$ with a matrix of size $N^2 \times N^2$
  $\Longrightarrow$ Complexity reduction from $\mathcal{O}(N^4)$ to $\mathcal{O}(N^3)$

2-d Transform used in JPEG

2-d block transform in JPEG

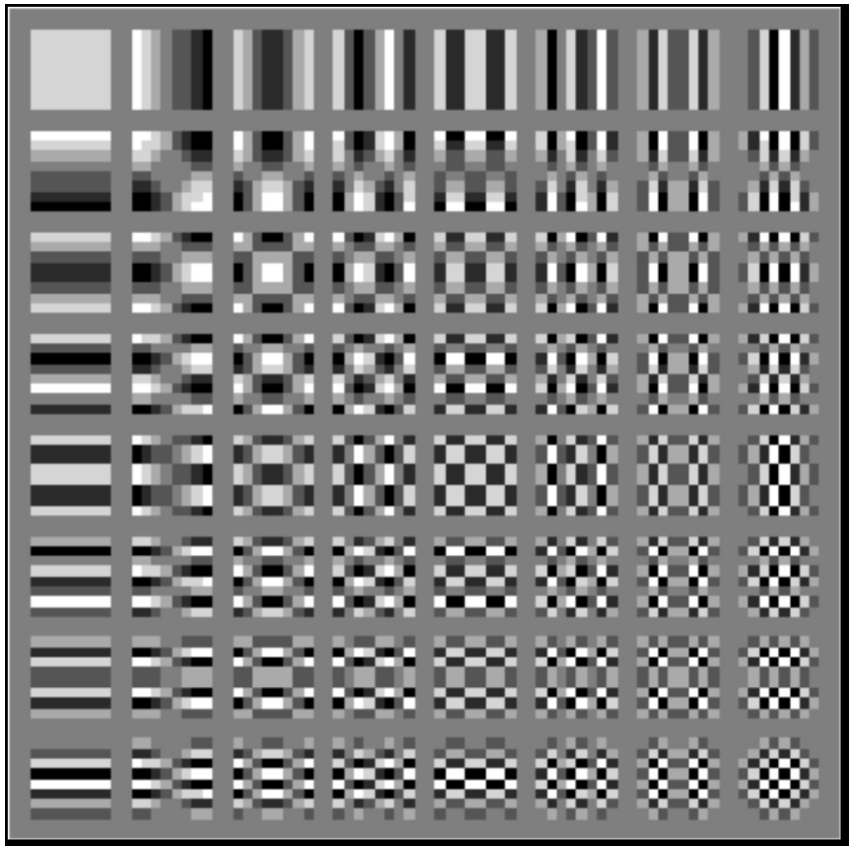
- Separable DCT of type II
- 8×8 transform matrix $\boldsymbol{A}$ consisting of elements a_{ik}, with $i, k = 0, \cdots, 7$, given by

$$a_{ik} = \alpha_i \cos \frac{\pi (2k+1) i}{16} \tag{590}$$

with

$$\alpha_i = \frac{1}{4} \begin{cases} 1 & : \quad i = 0 \\ \sqrt{2} & : \quad i > 0 \end{cases} \tag{591}$$

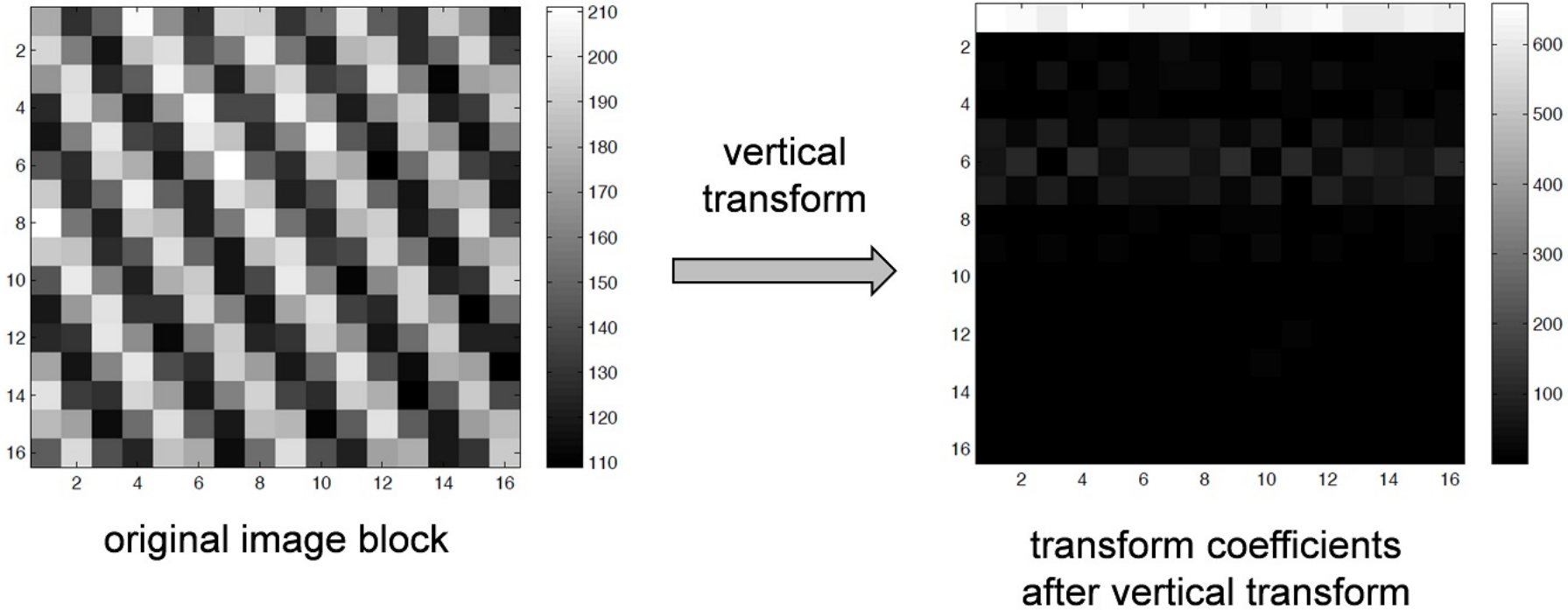
- Transform can be implemented using a fast butterfly algorithm



Transform specification in JPEG

- Ideal forward and backward transform are given in informative clause
- Specification contains normative accuracy requirements

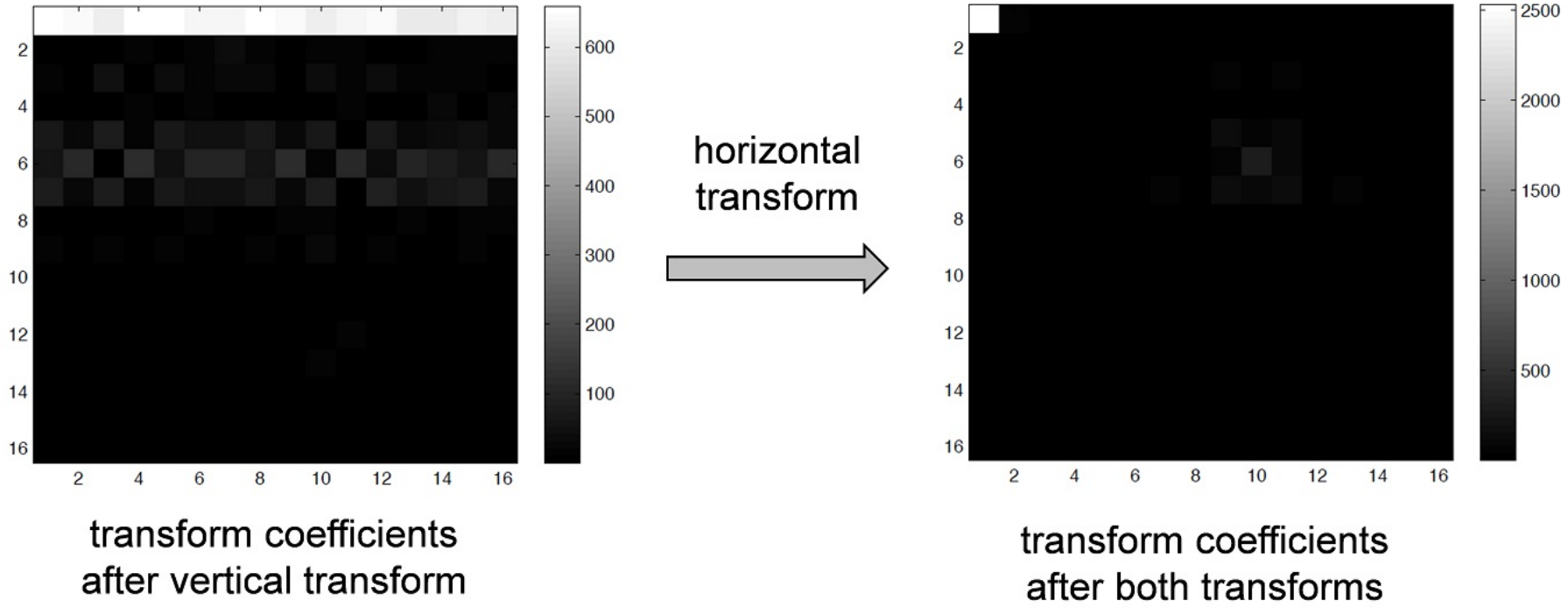
2-d DCT Example – Step 1: Vertical Transform



Example for a 16×16 DCT

- **Step 1**: Column-wise DCT on image block yielding intermediate block of transform coefficients
- Notice the energy concentration in the first row (DC coefficients)

2-d DCT Example – Step 2: Horizontal Transform



Example for a 16×16 DCT

- **Step 2**: Row-wise DCT on intermediate block of transform coefficients yielding the final block of DCT coefficients
- Notice the energy concentration in the DC coefficient (top-left)

Quantization in JPEG

JPEG specifies uniform reconstruction quantizers for the transform coefficients

- Inverse quantization (scaling) in decoder is specified by

$$t'_{ik} = \Delta_{ik} \cdot q_{ik} \tag{592}$$

with
q_{i_k} : Quantization index for coefficient at location (i, k) inside block
$\Delta_{i,k}$: Quantization step size for coefficient at location (i, k)
$t'_{i,k}$: Reconstructed transform coefficient at location (i, k)

- No normative encoding procedure, but informative quantization rule

$$q_{ik} = \mathrm{round}\left(\frac{t_{ik}}{\Delta_{ik}}\right) \qquad (t_{i,k}\text{: original transform coefficient}) \tag{593}$$

- Standard specifies accuracy requirements for combination of DCT and quantization
  $\Longrightarrow$ Leaves freedom for encoder designers
- Separate quantization step sizes can be selected for each coefficient location (i, k) and color component
  $\Longrightarrow$ Quantization tables have to be transmitted as side information (no defaults)
  $\Longrightarrow$ Additional freedom for encoder optimization

Quantization Tables in JPEG

Quantization tables

- Determine rate and distortion (among other parameters)
- Need to be transmitted (no default tables in JPEG)
- Example tables for YCbCr format are specified in Annex K of standard (empirically derived based on psychovisual threshold experiments)

luma blocks

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

chroma blocks

17	18	24	47	99	99	99	99
18	21	26	66	99	99	99	99
24	26	56	99	99	99	99	99
47	66	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99

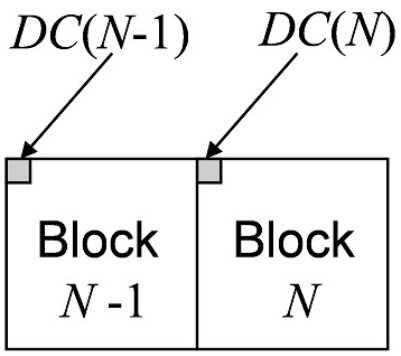
Entropy Coding in JPEG Baseline

Entropy coding of transform coefficient levels (quantization indices)

- Different concepts for DC and AC levels
- DC levels: Differential coding using codeword tables
- AC levels: Run-level coding of scanned coefficients

Coding of DC transform coefficient levels

- DC level is predicted by previous DC level as predictor
- Difference to predictor is coded using VLC and FLC
- Category C is coded using VLC
  - $\Longrightarrow$ Specifies range of values
  - $\Longrightarrow$ Specifies number of following bits (for FLC)
- FLC specifies actual value of *DIFF* inside category C
  - $\Longrightarrow$ If $DIFF > 0$, low-order bits of *DIFF*
  - $\Longrightarrow$ If $DIFF < 0$, low-order bits of $DIFF - 1$
- VLC table for category needs to be transmitted
  - $\Longrightarrow$ Increases side information (no default table)
  - $\Longrightarrow$ Allows adaptation to actual statistics



$DIFF = DC(N) - DC(N-1)$

Example VLC Table for Coding DC Difference Category

Example VLC table for coding category C

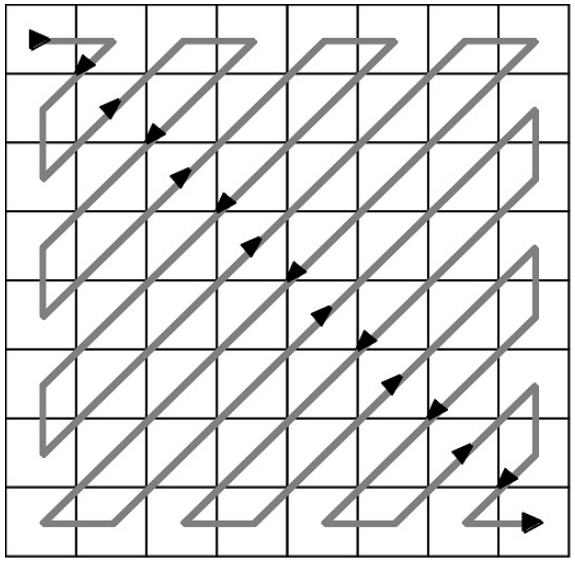
- Range of *DIFF* values is specified in standard
- Codeword assignment has to be transmitted
- Example shows recommended table for luma DC (Annex K of JPEG)

Category C	Range of *DIFF* value	Example codeword
0	0	00
1	-1, 1	010
2	-3, -2, 2, 3	011
3	-7..-4, 4..7	100
4	-15..-8, 8..15	101
5	-31..-16, 16..31	110
6	-63..-32, 32..63	1110
7	-127..-64, 64..127	11110
8	-255..-128, 128..255	111110
9	-511..-256, 256..511	1111110
10	-1023..-512, 512..1023	11111110
11	-2047..-1024, 1024..2047	111111110

Entropy Coding of AC Transform Coefficient Levels

Representation of AC levels

- Convert into sequence using a zig-zag scan
- AC coefficients are likely to be quantized to zero (in particular those at high-frequency locations)
- Successive runs of zeros are represented using a run (number of consecutive levels equal to zero)
- Non-zero AC levels are represented by a category and a value inside the category (same as for DC levels)



Coding of AC levels

- AC levels are coded using a combination of VLC and FLC
- Variable-length code table is used for coding events {run,category}
- VLC table includes a special symbol (EOB) for signaling the end-of-block (all remaining AC levels are equal to zero)
- Fixed-length code is used for coding the exact value inside a category (number of bits is given by category) – same as for DC difference levels
- VLC table has to be transmitted (no default table)

Example VLC Table for Run-Category Coding of AC Levels

Example for VLC table

- Standard defines ranges for categories (same as for DC, but no categories 0 and 11)
- Codeword assignment has to be transmitted
- Example shows first entries of recommended table for luma AC (Annex K of JPEG)

run/category	codeword
EOB	1010
0/1	00
0/2	01
0/3	100
0/4	1011
0/5	11010
0/6	1111000
0/7	11111000
0/8	1111110110
0/9	1111111110000010
0/10	1111111110000011
1/1	1100
1/2	11011
1/3	1111001
1/4	111110110
1/5	11111110110
1/6	1111111110000100
1/7	1111111110000101
1/8	1111111110000110
1/9	1111111110000111
1/10	1111111110001000

run/category	codeword
2/1	11100
2/2	11111001
2/3	1111110111
2/4	111111110100
2/5	1111111110001001
2/6	1111111110001010
2/7	1111111110001011
2/8	1111111110001100
2/9	1111111110001101
2/10	1111111110001110
3/1	111010
3/2	111110111
3/3	111111110101
3/4	1111111110001111
3/5	1111111110010000
3/6	1111111110010001
3/7	1111111110010010
3/8	1111111110010011
3/9	1111111110010100
3/10	1111111110010101
...	...

Example: JPEG Transform Coefficient Level Coding

Example for an 8×8 luma block:

- Last DC level: $DC(N-1) = 178$
- Use recommended luma tables

transform coefficient levels

185	3	1	0	-3	-1	0	0
1	0	-1	0	-2	0	0	0
0	0	0	-1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Coding of DC transform coefficient level

- Prediction difference: $DIFF = 185 - 178 = 7$
- Category $C = 3$: Codeword "100"
- Fixed-length code (lowest 3 bits of "7"): "111"
- Final bit representation (6 bit): "100111"

Coding of AC transform coefficient levels

- Zig-zag scanning and conversion into (run,level) pairs yields

$$(0,3)\ (0,1)\ (2,1)\ (1,-1)\ (6,-3)\ (0,-1)\ (0,-2)\ (0,-1)\ (\mathrm{EOB})$$

- Representation as (run,category) [FLC bits] sequence

$$(0,2)[11]\ (0,1)[1]\ (2,1)[1]\ (1,1)[0]\ (6,2)[00]\ (0,1)[0]\ (0,2)[01]\ (0,1)[0]\ (\mathrm{EOB})$$

- Bit sequence: VLC bits [FLC bits] (in total: 46 bits for 63 AC levels)

$$01\ [11]\ 00\ [1]\ 11100\ [1]\ 1100\ [0]\ 111111110110\ [00]\ 00\ [0]\ 01\ [01]\ 00\ [0]\ 1010$$

JPEG Compression Example – Original (YCbCr 4:2:0, 12 bpp)

JPEG Compression Example – 1:10 Compression (1.2 bpp)

JPEG Compression Example – 1:25 Compression (0.48 bpp)

JPEG Compression Example – 1:50 Compression (0.24 bpp)

JPEG Compression Example – 1:100 Compression (0.12 bpp)

JPEG Compression Example – 1:200 Compression (0.06 bpp)

Summary of JPEG

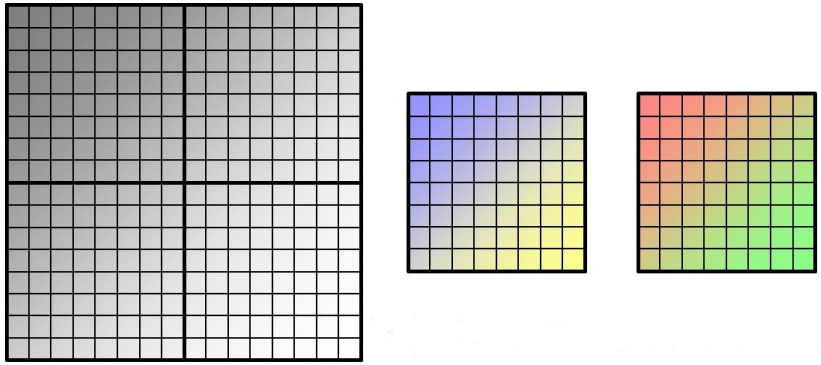
JPEG Baseline

- Minimum of capabilities (required for all DCT-based JPEG codecs)
- Source image: 1-4 color components with 8-bit per sample
- Sequential processing of 8×8 blocks
- Transform: Separable 8×8 discrete cosine transform (DCT) of type II
- Quantizer: Scalar uniform reconstruction quantizer (using quantization table)
- DC coding: Prediction and combination of VLC and FLC
- AC coding: Zig-zag scan and run-level coding (combination of VLC & FLC)
- VLC coding: 2 DC tables (category) & 2 AC tables (run/category)

Extended JPEG features

- Extended bit depth
- Adaptive binary arithmetic coding
- Progressive and hierarchical coding
- Lossless coding mode
- Extended file formats (e.g., EXIF)

Intra-Picture Coding in H.262 | MPEG-2 Video



Intra-Picture Coding in H.262 | MPEG-2 Video

H.262 | MPEG-2 Video

- Video coding standard jointly developed by ITU-T and ISO/IEC JTC 1
- Official name: ITU-T Rec. H.262 and ISO/IEC 13818-2
- Standard was finalized in 1994
- Still widely used in digital television and the DVD-Video optical disc format
- Three pictures types: I (intra), P (predictive) and B (bi-directional)
- Includes tools for interlaced video
- Most important conformance point: Main Profile
  - Color format: YCbCr 4:2:0
  - Bit depth: 8 bit per sample

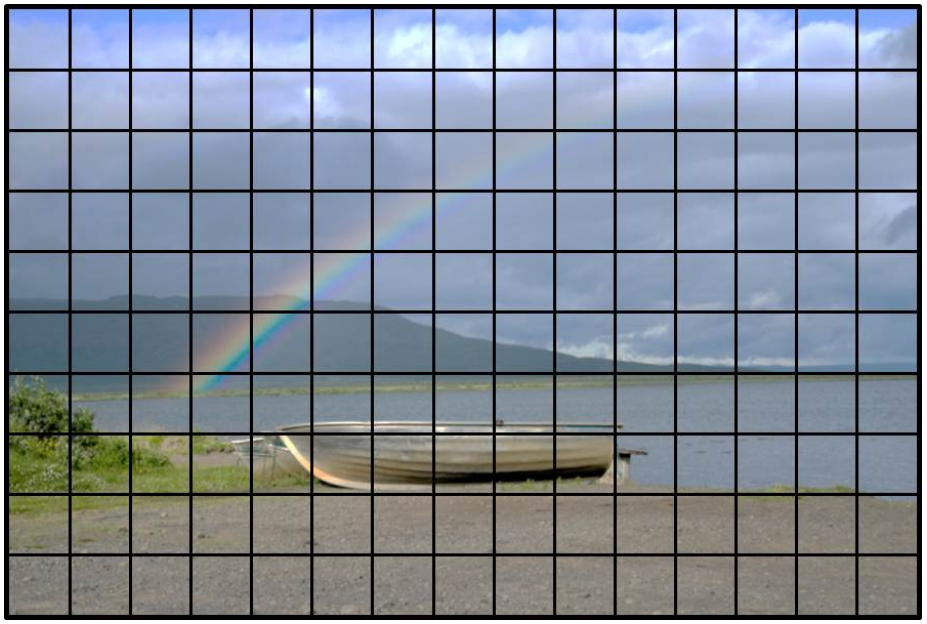
Intra-picture coding in H.262 | MPEG-2 Video

- Conceptually very similar to JPEG Baseline
- Details and actual syntax are different
- Fixed variable-length entropy coding tables

Macroblocks and Blocks in H.262 | MPEG-2 Video

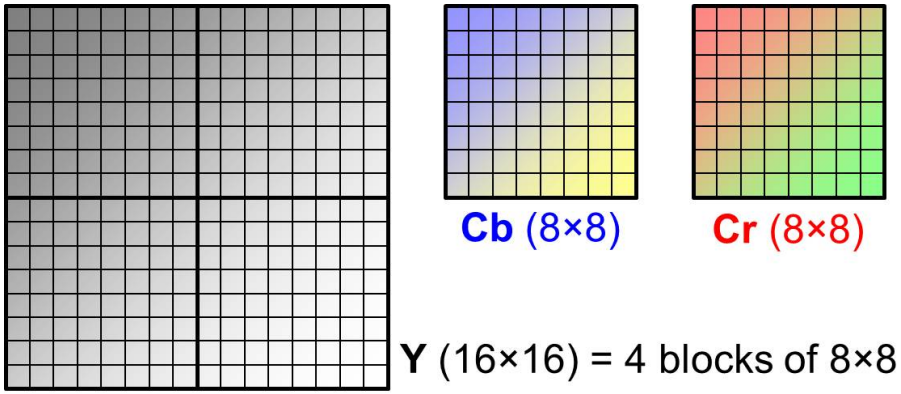
Picture partitioning into macroblocks

- Picture is partitioned into fixed-size **macroblocks**, which consist of 16×16 luma samples and the corresponding areas in the chroma components
- In 4:2:0 chroma sampling format, a macroblock corresponds to
  - one 16×16 luma block
  - two 8×8 chroma blocks

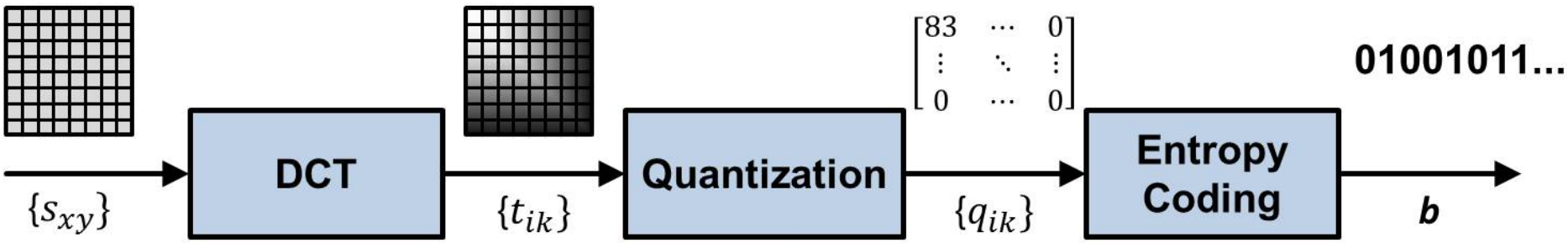


Coding of macroblocks

- Different **coding modes**, also referred to as **macroblock modes**
- Intra picture: 2 coding modes
  - Intra
  - Intra+Q (quantizer change)
- Intra mode: Transform coding for all six 8×8 **blocks** of a macroblock (4 luma and 2 chroma blocks)



Coding of 8×8 Intra Blocks in H.262 | MPEG-2 Video



Transform coding of 8×8 blocks

- Orthogonal block transform + scalar quantization + entropy coding
- Very similar to JPEG (but some differences in details)

Orthogonal block transform

- 2-d discrete coding transform (DCT) – same as in JPEG

Scalar quantization

- Quantization step size is specified by a quantization matrix and a quantization parameter (scaling for all coefficients, can be modified on macroblock basis)

Entropy coding of transform coefficient levels

- DC coefficient: Differential coding similar to JPEG
- AC coefficients: Zig-zag scan and run-level coding with EOB symbol

Quantization in H.262 | MPEG-2 Video

Standard specifies only construction of transform coefficients from levels

- Inverse quantization of intra DC coefficients (intra_dc_precision in range 8..11)

$$t'_{00} = q_{00} \cdot 2^{3-\text{intra\_dc\_precision}} \tag{594}$$

- Inverse quantization of AC coefficients in intra blocks

$$t'_{ik} = \text{sgn}(q_{ik}) \cdot \left\lfloor \frac{|q_{ik}| \cdot w_{ik} \cdot \text{QP}}{16} \right\rfloor \tag{595}$$

with
- q_{i_k} : Quantization index for coefficient at location (i,k) inside block
- $w_{i,k}$: Entry of quantization matrix for coefficient at location (i,k)
- QP : Quantization parameter (also called "quantizer_scale")
- $t'_{i,k}$: Reconstructed transform coefficient at location (i,k)

- Inverse quantization is followed by clipping to range $[-2048, 2047]$ and, thereafter, the so-called mismatch control operation

$$t'_{77} = \begin{cases} t'_{77} & : \quad s \text{ is odd} \\ t'_{77} - 1 & : \quad s \text{ is even and } t'_{77} \text{ is odd} \\ t'_{77} + 1 & : \quad s \text{ is even and } t'_{77} \text{ is even} \end{cases} \qquad \text{with} \quad s = \sum_{i=0}^{7} \sum_{k=0}^{7} t'_{ik} \tag{596}$$

Quantization Matrices in H.262 | MPEG-2 Video

Quantization matrices

- Quantization matrices define variation of quantizer step sizes among frequencies
  $\Longrightarrow$ Can be used for psychovisual optimization (to some extend)
- Quantization parameter QP is used for scaling the quantization matrices
  $\Longrightarrow$ Operation point can be modified on macroblock basis with a few bits
- For 4:2:0 data, two matrices are used: one for intra and one for non-intra
- Default quantization matrices can be replaced by user-defined matrices

default matrix for intra blocks

8	16	19	22	26	27	29	34
16	16	22	24	27	29	34	37
19	22	26	27	29	34	34	38
22	22	26	27	29	34	37	40
22	26	27	29	32	35	40	48
26	27	29	32	35	40	48	58
26	27	29	34	38	46	56	69
27	29	35	38	46	56	69	83

default matrix for non-intra blocks

16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16
16	16	16	16	16	16	16	16

Coding of Transform Coefficients Levels for Intra 8×8 Blocks

DC transform coefficient level in intra blocks

- Very similar to JPEG
- Prediction using last coded DC level (reset at start of slice or non-intra MB)
- Difference is coded by a category (called dct_dc_size) a fixed-length code
- Entropy coding table is fixed in standard (cannot be modified)

AC transform coefficient levels

- Levels of a block are converted into vector using a zig-zag scan (same as in JPEG)
- Vector of levels is coded using **run-level code**
  - Entropy coding table for most frequent combinations of run and level (actual levels including sign, not categories as in JPEG)
  - Includes **end-of-block** (EOB) symbol
  - Includes **escape** symbol for less likely combinations, for which the actual run and level are transmitted with 6 and 12 bit, respectively
- Entropy coding tables are fixed in standard (cannot be modified)
- For intra, one of two defined tables can be selected on a picture basis

Encoder Control for Intra Pictures in H.262 | MPEG-2 Video

What parameters can be chosen in encoder?

- On sequence/picture level: Quantization matrix, intra vlc table, intra DC precision
- On macroblock level: Quantization parameter QP
- On block level: Transform coefficient levels

$\Longrightarrow$ **Transform coefficient levels have largest impact on coding efficiency**

Do the parameters of different blocks influence each other?

- Only last DC coefficient is used for prediction
- Typically very small impact on coding efficiency

$\Longrightarrow$ **Interdependencies between blocks can be neglected**

How can the selection of transform coefficient levels be optimized?

- Selection determines distortion and rate!
- Rounding to next level minimizes distortion, but typically produces a large rate
- For an operation point given by a Lagrange parameter λ, the combined cost measure $D + \lambda \cdot R$ should be minimized
- Not straightforward due to run-level coding

$\Longrightarrow$ **Need to consider dependencies in coding of successive levels**

$\Longrightarrow$ **Fixed decision levels cannot be optimal**

Example: Impact of Considering Rate in Quantization

Quantization example with $\Delta = 10$ and $\lambda = 10$

- Consider quantization of the following vector of transform coefficients

36	18	23	3	12	-4	-3	2	-6	0	···	0

- Rounding to nearest quantization level according to $q = \mathrm{round}(c/\Delta)$ yields

4	2	2	0	1	0	0	0	-1	0	···	0

$\Longrightarrow$ Sequence of (run,level) values: (0,4)(0,2)(0,2)(1,1)(3,-1)(EOB)

$\Longrightarrow$ Bit sequence: (00001100)(01000)(01000)(0110)(001111)(10)

$\Longrightarrow$ Distortion $D = 87$, rate $R = 30$ $\quad\Longrightarrow\quad$ $J = D + \lambda \cdot R = 387$

- Alternative quantization (considering rate by minimizing $J = D + \lambda \cdot R$)

4	2	2	0	1	0	0	0	0	0	···	0

$\Longrightarrow$ Sequence of (run,level) values: (0,4)(0,2)(0,2)(1,1)(EOB)

$\Longrightarrow$ Bit sequence: (00001100)(01000)(01000)(0110)(10)

$\Longrightarrow$ Distortion $D = 107$, rate $R = 24$ $\quad\Longrightarrow\quad$ $J = D + \lambda \cdot R = 347\ (< 387)$

Rate-Distortion Optimized Quantization (RDOQ)

General idea of rate-distortion optimized quantization for run-level coding

- Evaluate "all possible" vectors of transform coefficient levels
- Choose vector that minimizes $J = D + \lambda \cdot R$, with
  - D: Distortion for block (can be measured in transform domain)
  - R: Rate for transmitting levels using given entropy coding tables
  - λ: Lagrange parameter, e.g., given as function of quantization parameter QP

$\Longrightarrow$ Very complex: Require restriction for levels and suitable algorithm

Select reasonable set of potential levels for each coefficient

- Following observations can be made (considering absolute levels)
  - Levels greater than the level obtained by mathematically correct rounding don't need to be considered (larger distortion and larger rate)
  - Levels that are significantly smaller than the level obtained by mathematically correct rounding don't need to be considered (very large distortion)
- Good compromise is obtained by following set of 1-3 levels (absolute values)
  - Level q_0 obtained by mathematically correct rounding, $q_0 = \mathrm{round}(c/\Delta)$
  - Level q_1 obtained by rounding towards zero, $q_1 = \lfloor c/\Delta \rfloor$
  - If $q_1 > 1$, level $q_2 = q_1 - 1$

RDOQ Algorithm for Run-Level Coding

Start with first position $k = 0$ in scanning order

- For all potential levels $\{q_0\}$ determine
  - distortion $D_0 = (c_0 - q_0 \cdot \Delta)^2$
  - for non-zero levels q_0, rate R_0 using run-level coding tables
- Among all non-zero levels q_0, keep only the one that minimizes $J_0 = D_0 + \lambda \cdot R_0$
- At most two candidate vectors $\boldsymbol{q}_0 = [q_0]$ are considered for the further steps, one with $q_0 = 0$ and one with $q_0 \neq 0$

For each of the remaining positions k in scanning order

- Combine all potential levels $\{q_k\}$ for current position k with the selected candidate vectors $\boldsymbol{q}_{k-1}$ to new candidate vectors $\boldsymbol{q}_k$ and determine
  - distortion $D_k = D_{k-1} + (c_k - q_k \cdot \Delta)^2$
  - for non-zero levels q_k, rate R_k using run-level coding tables
- Among all vectors $\boldsymbol{q}_k$ with the last level q_k unequal to 0, discard all vectors except the one that minimizes $D_k + \lambda \cdot R_k$

After last scanning position k

- Determined the final cost $J = D + \lambda \cdot R$ for all remaining candidate vectors $\boldsymbol{q}$ (including EOB symbol) and choose the one that minimizes J

RDOQ Example

Simple RDOQ example using quantization step size $\Delta = 10$ and $\lambda = 10$

- Consider transform coefficient vector of 9 coefficients

36	18	23	3	12	-4	-3	2	-6

- Coefficient "36" at position $k = 0$ with potential levels $\{4, 3, 2\}$:
  - $\Rightarrow$ $[\mathbf{4}]$: $D = 4^2 = 16$, $R = 8$ $\rightarrow$ $J = 96$
  - $\Rightarrow$ $[\mathbf{3}]$: $D = 6^2 = 36$, $R = 6$ $\rightarrow$ $J = 96$ [discard]
  - $\Rightarrow$ $[\mathbf{2}]$: $D = 16^2 = 256$, $R = 5$ $\rightarrow$ $J = 306$ [discard]
- Coefficient "18" at position $k = 1$ with potential levels $\{2, 1, 0\}$:
  - $\Rightarrow$ $[4, \mathbf{2}]$: $D = 16 + 2^2 = 20$, $R = 8 + 5 = 13$ $\rightarrow$ $J = 150$
  - $\Rightarrow$ $[4, \mathbf{1}]$: $D = 16 + 8^2 = 80$, $R = 8 + 3 = 11$ $\rightarrow$ $J = 190$ [discard]
  - $\Rightarrow$ $[4, \mathbf{0}]$: $D = 16 + 18^2 = 340$, $R = 8$ (does not include last zero)
- Coefficient "23" at position $k = 2$ with potential levels $\{2, 1\}$:
  - $\Rightarrow$ $[4, 2, \mathbf{2}]$: $D = 20 + 3^2 = 29$, $R = 13 + 5 = 18$ $\rightarrow$ $J = 209$
  - $\Rightarrow$ $[4, 2, \mathbf{1}]$: $D = 20 + 13^2 = 189$, $R = 13 + 3 = 16$ $\rightarrow$ $J = 349$ [discard]
  - $\Rightarrow$ $[4, 0, \mathbf{2}]$: $D = 340 + 3^2 = 349$, $R = 8 + 7 = 15$ $\rightarrow$ $J = 499$ [discard]
  - $\Rightarrow$ $[4, 0, \mathbf{1}]$: $D = 340 + 13^2 = 509$, $R = 8 + 4 = 12$ $\rightarrow$ $J = 629$ [discard]
- Coefficient "3" at position $k = 3$ with potential levels $\{0\}$:
  - $\Rightarrow$ $[4, 2, 2, \mathbf{0}]$: $D = 29 + 3^2 = 38$, $R = 18$ (without trailing zeros)

RDOQ Example (continued)

- Coefficient "12" at position $k = 4$ with potential levels $\{1, 0\}$:
  - $\Rightarrow$ $[4, 2, 2, 0, \mathbf{1}]$: $D = 38 + 2^2 = 42$, $R = 18 + 4 = 22$ $\rightarrow$ $J = 262$
  - $\Rightarrow$ $[4, 2, 2, 0, \mathbf{0}]$: $D = 38 + 12^2 = 182$, $R = 18$ (without trailing zeros)
- Coefficient "-4" at position $k = 5$ with potential levels $\{0\}$:
  - $\Rightarrow$ $[4, 2, 2, 0, 1, \mathbf{0}]$: $D = 42 + 4^2 = 58$, $R = 22$ (without trailing zeros)
  - $\Rightarrow$ $[4, 2, 2, 0, 0, \mathbf{0}]$: $D = 182 + 4^2 = 198$, $R = 18$ (without trailing zeros)
- Coefficient "-3" at position $k = 6$ with potential levels $\{0\}$:
  - $\Rightarrow$ $[4, 2, 2, 0, 1, 0, \mathbf{0}]$: $D = 58 + 3^2 = 67$, $R = 22$ (without trailing zeros)
  - $\Rightarrow$ $[4, 2, 2, 0, 0, 0, \mathbf{0}]$: $D = 198 + 3^2 = 207$, $R = 18$ (without trailing zeros)
- Coefficient "2" at position $k = 7$ with potential levels $\{0\}$:
  - $\Rightarrow$ $[4, 2, 2, 0, 1, 0, 0, \mathbf{0}]$: $D = 67 + 2^2 = 71$, $R = 22$ (without trailing zeros)
  - $\Rightarrow$ $[4, 2, 2, 0, 0, 0, 0, \mathbf{0}]$: $D = 207 + 2^2 = 211$, $R = 18$ (without trailing zeros)
- Last coefficients "-6" with potential levels $\{-1, 0\}$ (including 2 bits for EOB):
  - $\Rightarrow$ $[4, 2, 2, 0, 1, 0, 0, 0, -\mathbf{1}]$: $D = 71 + 4^2 = 87$, $R = 22 + 8 = 30$ $\rightarrow$ $J = 387$
  - $\Rightarrow$ $[4, 2, 2, 0, 1, 0, 0, 0, \mathbf{0}]$: $D = 71 + 6^2 = 107$, $R = 22 + 2 = 24$ $\rightarrow$ $J = 347$
  - $\Rightarrow$ $[4, 2, 2, 0, 0, 0, 0, 0, -\mathbf{1}]$: $D = 211 + 4^2 = 227$, $R = 18 + 9 = 27$ $\rightarrow$ $J = 497$
  - $\Rightarrow$ $[4, 2, 2, 0, 0, 0, 0, 0, \mathbf{0}]$: $D = 211 + 6^2 = 247$, $R = 18 + 2 = 20$ $\rightarrow$ $J = 447$

$\Longrightarrow$ Selected transform coefficient levels: $[4, 2, 2, 0, 1, 0, 0, 0, 0]$ with $J = 347$

$\Longrightarrow$ For comparison, rounding would yield: $[4, 2, 2, 0, 1, 0, 0, 0, -1]$ with $J = 387$

Experimental Analysis of RDOQ for Intra-Picture Coding

Coding experiment with H.262 | MPEG-2 Video comparing

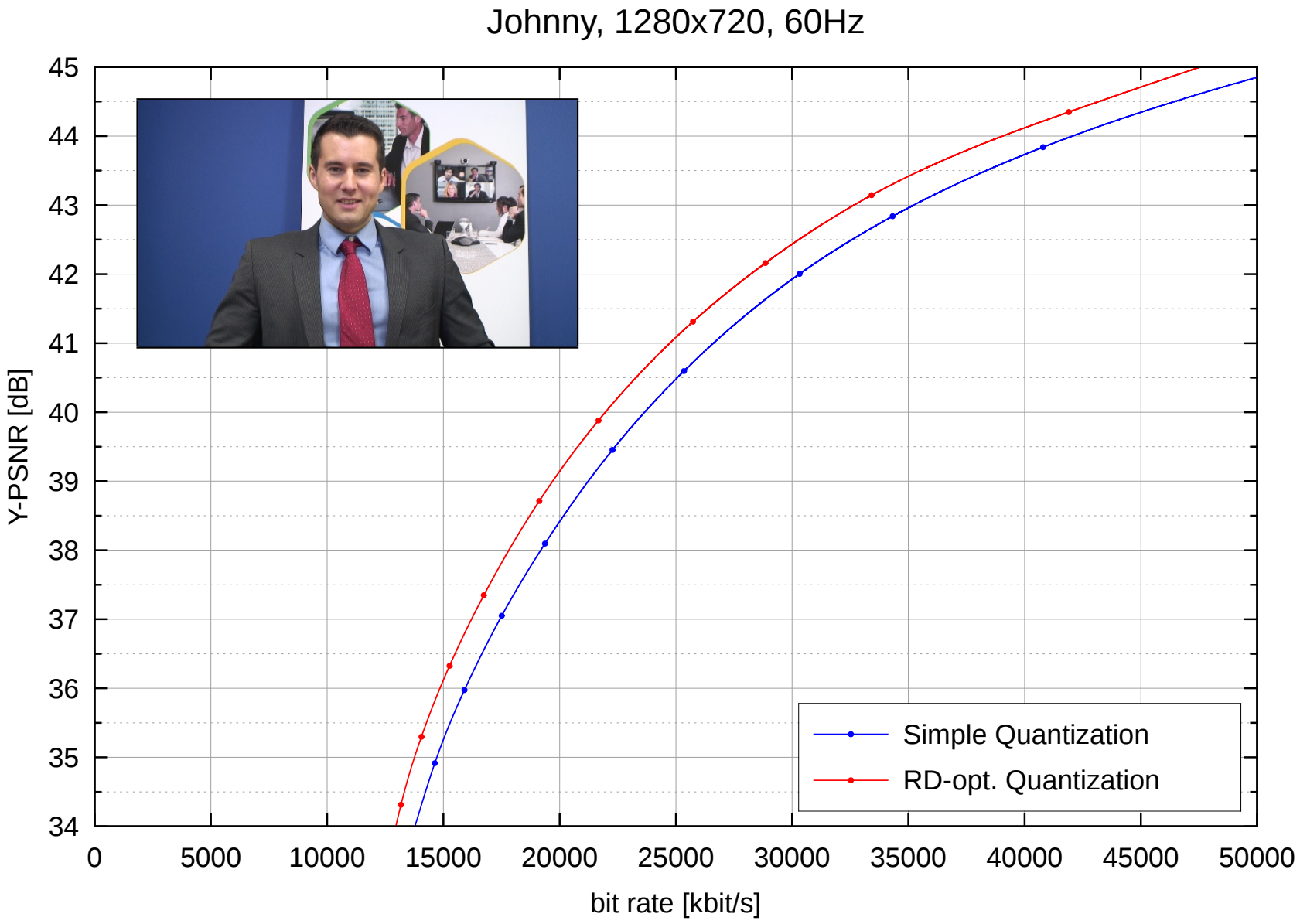
- Encoder with simple quantization using mathematically correct rounding
- Encoder using rate-distortion optimized quantization

Coding conditions

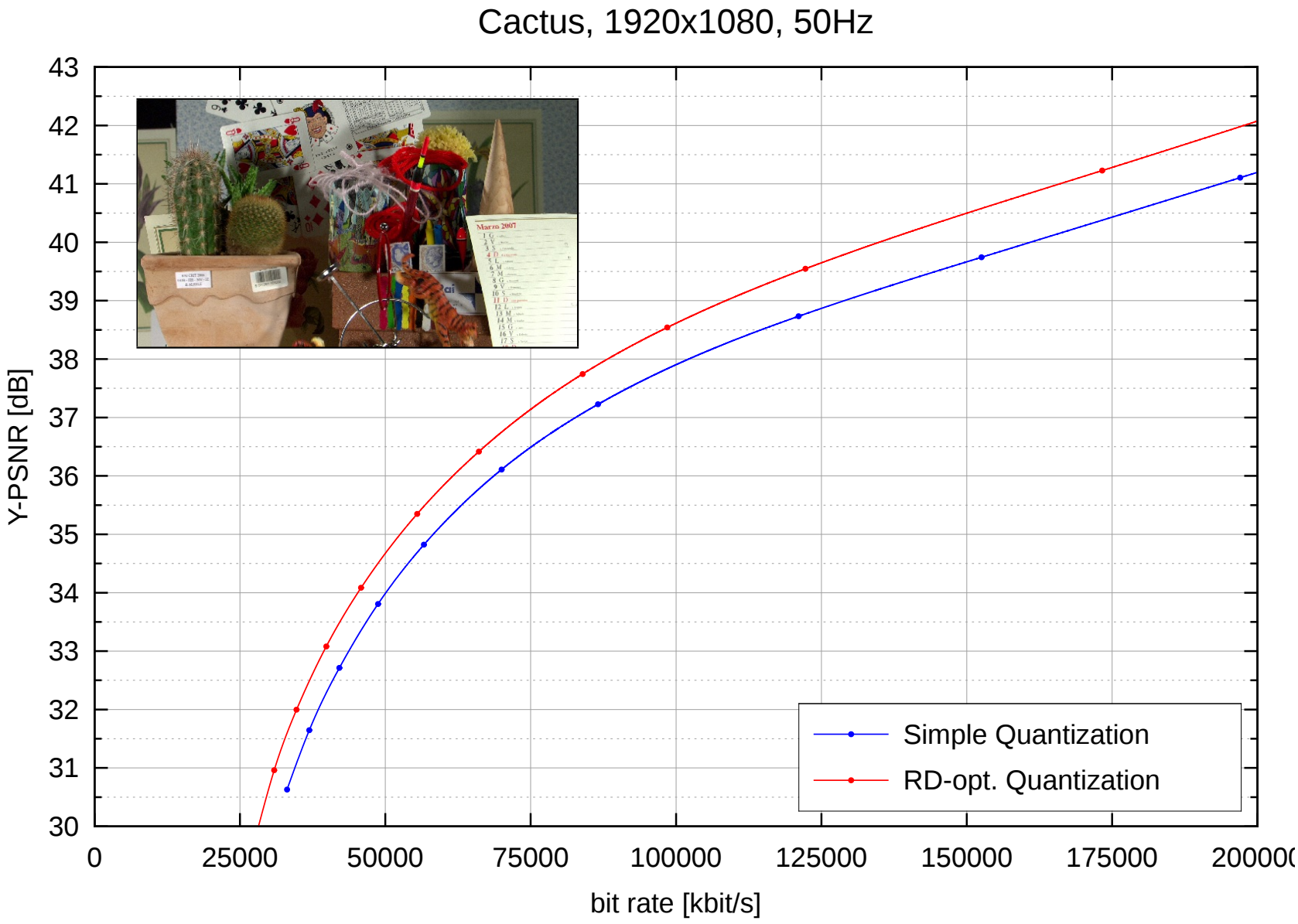
- 6 video conferencing sequences with a resolution of 1280×720
- 6 more complex video sequences with a resolution of 1920×1080
- 10 pictures of each sequence have been coded (intra only)
- Flat quantization matrices (since quality is measured using PSNR)
- Same quantization parameter for all macroblocks
- Bitstreams with different quantization parameters
- PSNR and rate have been measured
- Lagrange parameter λ has been coupled to quantization step size Δ using the experimentally determined relationship

$$\lambda = \text{const} \cdot \Delta^2$$

Quantization Comparison – Sequence "Johnny"



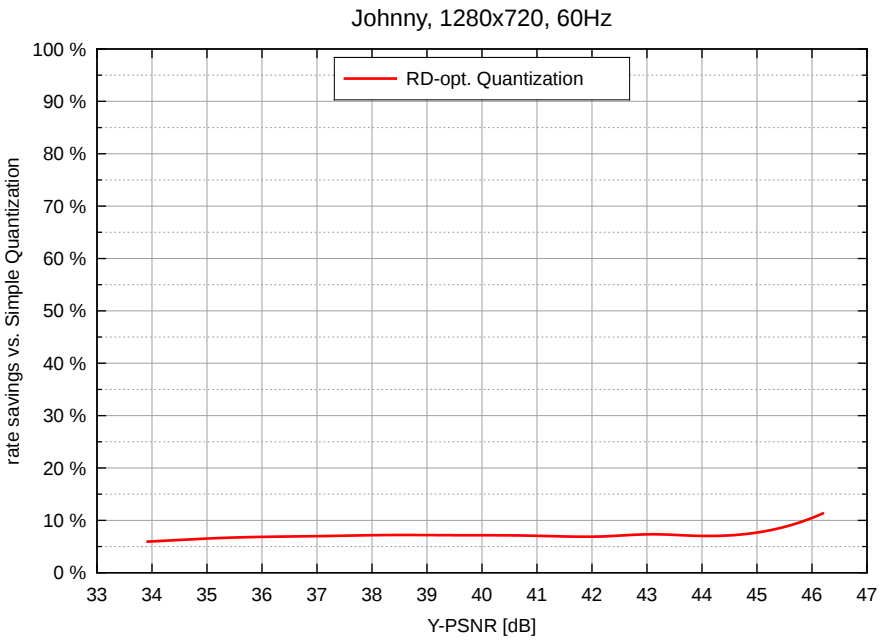
Quantization Comparison – Sequence "Cactus"

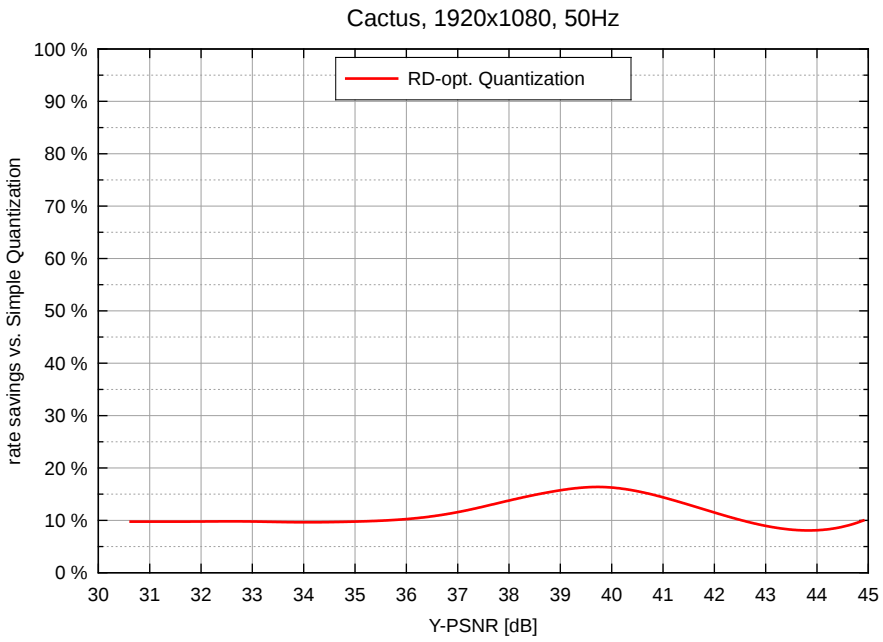


Quantization Comparison – Summary

Bit-rate savings of RDOQ versus simple quantization

- Bit-rate saving at a PSNR value is obtained by interpolating the r-d curves
- Average bit-rate savings are obtained by averaging the savings for 100 PSNR values
- Average bit-rate saving for all sequences: 9%





Summary of Intra-Picture Coding in H.262 | MPEG-2 Video

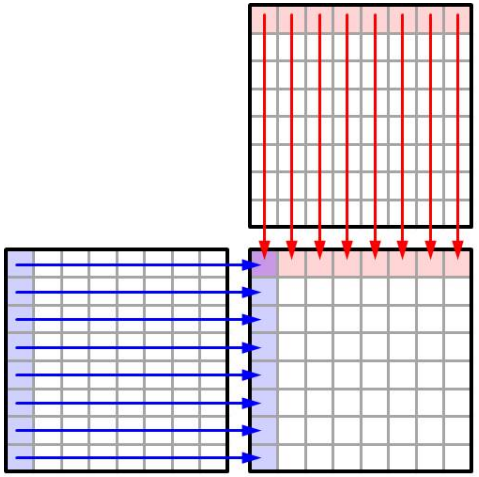
Intra-picture coding in H.262 | MPEG-2 Video

- Video coding standard of ITU-T and ISO/IEC JTC 1
- Still widely used in digital television and DVD-Video
- Intra-picture coding is very similar to JPEG Baseline
- Picture partitioning in macroblocks and blocks
- Scalar quantization of transform coefficients
- Quantization matrices are combined with quantization parameter
- Run-level coding for transform coefficients

Rate-distortion optimized quantization

- Quantization with fixed decision levels cannot be optimal due to dependencies in run-level entropy coding
- Actual rate for coding transform coefficient levels need to be considered
- Optimal quantization can be achieved by a trellis-like procedure
- Rate-distortion optimized quantization yields average bit-rate savings of about 10% relative to simple rounding (for intra-only coding)

Intra-Picture Coding in H.263 and MPEG-4 Visual



ITU-T Recommendation H.263 – Overview

ITU-T Recommendation H.263

- Video coding standard of ITU-T
- Developed by Visual Coding Experts Group (VCEG – ITU-T SG16/WP3/Q6)
- Primarily designed for low bit-rate video conferencing
- Example applications:
  - Video conferencing
  - Was used for Flash Video content
  - RealVideo codec (before RealVideo 8) was based on H.263
- First version (1995)
  - Very similar structure as H.262 | MPEG-2 Video
  - Several improvements relative to H.262 | MPEG-2 Video
  - For intra: Run-level-last coding and optimized coding tables
- Second version H.263+ (1998)
  - Improvements and new features
  - For intra: AC level prediction, adaptive scans, specialized quantization and entropy coding tables for intra blocks
- Third version H.263++ (2000)
  - Multiple reference pictures for motion-compensated coding

Intra-Picture Coding in H.263 Baseline

Basic design for intra-picture coding – similar to H.262 | MPEG-2 Video

- Partitioning into 16×16 macroblocks as in H.262 | MPEG-2 Video
- Transform coding of 8×8 blocks (DCT + scalar quantization + entropy coding)

Orthogonal block transform

- Same separable 8×8 DCT as in H.262 | MPEG-2 Video and JPEG

Scalar quantization of transform coefficients (only reconstruction is specified)

- Step size determined by quantization parameter QP (can be modified on MB basis)
- DC coefficient (uniform reconstruction quantizer)

$$t'_{00} = 8 \cdot q_{00} \tag{597}$$

- AC coefficients (uniform reconstruction quantizer with extra-wide deadzone)

$$t'_{ik} = \begin{cases} 0 & : \quad q_{ik} = 0 \\ \mathrm{sgn}(q_{ik}) \cdot \mathrm{QP} \cdot (2 \cdot |q_{ik}| + 1) & : \quad q_{ik} \neq 0 \text{ and QP is odd} \\ \mathrm{sgn}(q_{ik}) \cdot \mathrm{QP} \cdot (2 \cdot |q_{ik}| + 1) - 1 & : \quad q_{ik} \neq 0 \text{ and QP is even} \end{cases} \tag{598}$$

$\Longrightarrow$ Reconstructed levels are always odd-valued numbers (except zero)

$\Longrightarrow$ Has been found to prevent accumulation of IDCT mismatches (for inter)

Coding of Transform Coefficient Levels in H.263 Baseline

Coded block pattern (CBP)

- Signal which 8×8 blocks of a macroblock contain non-zero levels (AC levels)
- Concept was also used in H.262 | MPEG-2 Video, but only for inter macroblocks
- Required for run-level-last coding of AC levels
- In H.263, split into two components:
  - CBPC (two bits for the chroma blocks): Coded together with MB type
  - CBPY (four bits for the luma blocks): Coded as separate codeword

MB type	CBPC	codeword
Intra	00	1
Intra	01	001
Intra	10	010
Intra	11	011
Intra+Q	00	0001
Intra+Q	01	0000 01
Intra+Q	10	0000 10
Intra+Q	11	0000 11
stuffing	–	0000 0000 1

CBPY	codeword	CBPY	codeword
0000	0011	1000	0001 0
0001	0010 1	1001	0000 11
0010	0010 0	1010	0101
0011	1001	1011	1010
0100	0001 1	1100	0100
0101	0111	1101	1000
0110	0000 10	1110	0110
0111	1011	1111	11

Coding of DC transform coefficient level

- No prediction of DC coefficient (in contrast to JPEG and H.262 | MPEG-2 Video)
- Fixed-length code: 8 bit per DC level

Coding of AC Transform Coefficient Levels in H.263 Baseline

Coding of AC transform coefficient levels

- Convert matrix of AC levels to vector using the zig-zag scan
- Vector of AC levels is coded using **run-level-last code**
- Entropy coding table for most common combinations of
  - Run: Number of preceding levels equal to zero
  - Level: Value of the next non-zero level
  - Last: Flag indicating if the non-zero level is the last non-zero level in block
- Entropy coding table includes an **escape** symbol for less likely combinations, for which the "run", "level" and "last" are coded using fixed-length codes (6+8+1 bit)
- Entropy coding tables have been optimized for low rates

last	run	level	codeword (s = sign)
0	0	± 1	10s
0	0	± 2	1111 s
0	0	± 3	0101 01s
0	0	± 4	0010 111s
0	0	± 5	0001 1111 s
0	0	± 6	0001 0010 1s
0	0	± 7	0001 0010 0s
0	0	± 8	0000 1000 01s
0	0	± 9	0000 1000 00s
0	0	± 10	0000 0000 111s
0	0	± 11	0000 0000 110s
0	0	± 12	0000 0100 000s

last	run	level	codeword (s = sign)
...	...	...	...
1	31	± 1	0000 0100 110s
1	32	± 1	0000 0100 111s
1	33	± 1	0000 0101 1000 s
1	34	± 1	0000 0101 1001 s
1	35	± 1	0000 0101 1010 s
1	36	± 1	0000 0101 1011 s
1	37	± 1	0000 0101 1100 s
1	38	± 1	0000 0101 1101 s
1	39	± 1	0000 0101 1110 s
1	40	± 1	0000 0101 1111 s
	escape		0000 011

Advanced Intra Coding Mode in Annex I of H.263+

Advanced intra-picture coding mode (in optional Annex I) specifies

- Adaptive prediction of transform coefficients in intra blocks
- Adaptive scanning of transform coefficient levels (depending on prediction)
- Modified inverse quantization for intra
- Separate entropy coding table for intra blocks (optimized for intra)

Adaptive prediction and scanning

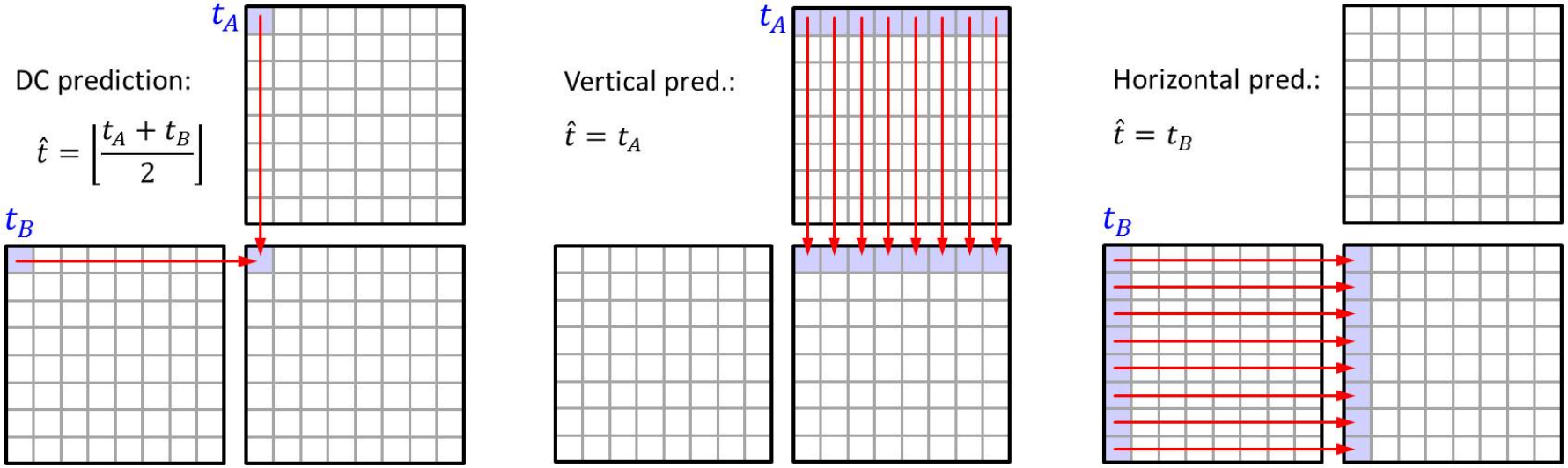
- Predict part of the transform coefficients using reconstructed transform coefficients of neighboring blocks of same color component
- Quantization and entropy coding of prediction residuals $t_{ik} - \hat{t}_{ik}$

$$t'_{ik} = \hat{t}_{ik} + Q^{-1}(q_{ik}) \qquad (Q^{-1}\text{: inverse quantization}) \tag{599}$$

- 3 prediction modes (signaled at macroblock level)
  - DC prediction: Predict DC using left and above neighboring block
  - Vertical prediction: Predict first row of coefficients using above block
    $\Longrightarrow$ Particularly suitable for vertical structures
  - Horizontal prediction: Predict first column of coefficients using left block
    $\Longrightarrow$ Particularly suitable for horizontal structures

Prediction Modes for Intra Blocks in Advanced Intra Coding

Prediction of transform coefficients: 3 modes signaled at macroblock level



Modified quantization for intra macroblocks

- Use same quantization for all coefficients (including DC coefficient)
- Uniform reconstruction quantizer without extra-wide deadzone and without mismatch control (only important for inter macroblocks)

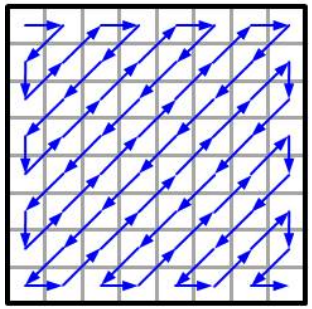
$$t'_{ik} = 2 \cdot \mathrm{QP} \cdot q_{ik}, \qquad \forall i, k = 0..7 \tag{600}$$

Entropy Coding in Advanced Intra Coding Mode

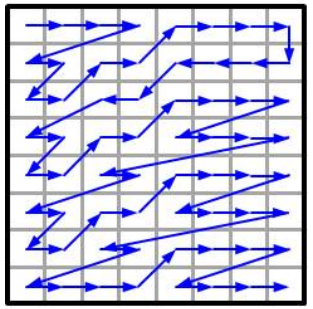
Scanning pattern is chosen based on prediction mode

- Goal: Concentrate zero levels at end of scanning pattern
- Non-zero coefficient distribution is depending on prediction mode
  - DC prediction: Conventional zig-zag scan
  - Vertical prediction: Horizontal scan (suitable for vertical structures)
  - Horizontal prediction: Vertical scan (suitable for horizontal structures)

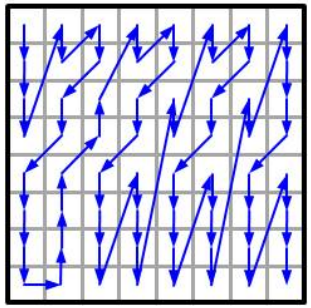
zig-zag scan
(DC pred.)



horizontal scan
(vertical pred.)



vertical scan
(horizontal pred.)



Coding of vector of transform coefficient levels

- No separate coding of DC coefficient $\Longrightarrow$ included in run-level-last code
- Entropy coding table for run-level-last code optimized for intra statistics

Further Extensions in H.263 for Improving Intra Coding

Annex E: Syntax-based arithmetic coding

- Specifies non-adaptive arithmetic coding for syntax elements
- Rarely used in practice

Annex J: Deblocking filter mode

- Specifies deblocking filter for reducing block-edge artifacts
- Strength of smoothing filter is controlled by quantization parameter
- Most useful for coding of following inter pictures, but also improves quality of intra pictures at low rates

Annex T: Modified quantization mode

- Improves ability to control bit rate (finer steps for modifying QP)
- Extends range of representable transform coefficient values
- Improves chroma fidelity by choosing smaller quantization step size for chroma than for luma (particularly for low rates)

Intra-Picture Coding in MPEG-4 Visual

International standard ISO/IEC 14496-2 (MPEG-4 Visual)

- Video coding standard of Moving Pictures Experts Group (MPEG)
- Includes H.263 Baseline decoder, contains several extensions
- Was used in digital cameras, DivX, ...

Coding of intra macroblocks

- Prediction of transform coefficients (similar to H.263 Annex I)
  - DC level is always predicted from left or above block (direction is determined by differences of neighboring DC levels)
  - First row/column of ACs can be optionally predicted using same prediction direction as for DC (usage is signaled at macroblock level)
- Two methods for quantization
  - MPEG-style: Quantization as in MPEG-2 Video (including weighting matrix)
  - H263-style: Quantization as in H.263 Baseline
- Scanning of transform coefficients
  - 3 scans: Zig-zag, horizontal, vertical (chosen based on prediction mode)
- Coding of vector of transform coefficient levels
  - Coded block pattern and run-level-last coding

Encoder Control for Intra Coding in H.263 and MPEG-4 Visual

Increased degree of freedom relative to H.262 | MPEG-2 Video

- In addition to transform coefficient levels, the method for transform coefficient selection can be selected on macroblock level
- H.263 (Annex I): DC, vertical or horizontal prediction mode
- MPEG-4 Visual: DC or DC and AC prediction

Rate-distortion optimized encoder control

- Determine bitstream $\boldsymbol{b}$ so that the distortion $D(\boldsymbol{s}, \boldsymbol{s}')$ between original picture $\boldsymbol{s}$ and reconstructed picture $\boldsymbol{s}'$ is minimized given a particular target rate $R \leq R_{\text{target}}$
- With $\mathcal{B}_c$ being the set of *conforming* bitstreams with $R \leq R_{\text{target}}$, we can write

$$\boldsymbol{b}^* = \arg\min_{\boldsymbol{b} \in \mathcal{B}_c} D\big(\boldsymbol{s}, \boldsymbol{s}'(\boldsymbol{b})\big) \tag{601}$$

  $\Longrightarrow$ Not feasible due to huge parameter space
  $\Longrightarrow$ Split into smaller optimization problems by partially ignoring dependencies
- Consider block of samples $\boldsymbol{s}_k$ (e.g., picture or macroblock) and optimize with respect to coding parameters $\boldsymbol{p}_k$ (e.g., modes and transform coefficient levels)

$$\min_{\boldsymbol{p}_k} D\big(\boldsymbol{s}_k, \boldsymbol{s}'_k(\boldsymbol{p}_k)\big) \qquad \text{subject to} \qquad R(\boldsymbol{p}_k) \leq R_c \tag{602}$$

Rate-distortion optimized encoder control

Lagrangian encoder control

- Constrained optimization problem for a block of samples $\boldsymbol{s}_k$

$$\min_{\boldsymbol{p}_k} D\big(\boldsymbol{s}_k, \boldsymbol{s}'_k(\boldsymbol{p}_k)\big) \qquad \text{subject to} \qquad R(\boldsymbol{p}_k) \leq R_c \tag{603}$$

  can be reformulated as unconstrained optimization problem

$$\min_{\boldsymbol{p}_k} D\big(\boldsymbol{s}_k, \boldsymbol{s}'_k(\boldsymbol{p}_k)\big) + \lambda \cdot R(\boldsymbol{p}_k) \tag{604}$$

- Consider partition of $\boldsymbol{s}_k$ into a number of subsets $\boldsymbol{s}_{k,i}$ (e.g. macroblocks)
- If coding parameters $\boldsymbol{p}_{k,i}$ are independent of each other and an additive distortion measure is used, we can write the optimization problem as

$$\sum_i \min_{\boldsymbol{p}_{k,i}} D\big(\boldsymbol{s}_{k,i}, \boldsymbol{s}'_{k,i}(\boldsymbol{p}_{k,i})\big) + \lambda \cdot R(\boldsymbol{p}_{k,i}) \tag{605}$$

  $\Longrightarrow$ Independent selection of coding parameters $\boldsymbol{p}_{k,i}$
- For coding decisions in image and video coding
  - Coding decisions are typically not independent (e.g., due to prediction)
  - For practical applicability: Consider past decisions, but ignore impact on future

Lagrangian Encoder Control in Image and Video Coding

Application of Lagrangian encoder control

- Can be applied to basically all decisions in an encoder
- **Quantization**: Select vector $\boldsymbol{q}$ of transform coefficient levels according to

$$\boldsymbol{q}^* = \arg\min_{\boldsymbol{q}} \; D(\boldsymbol{q}) + \lambda \cdot R(\boldsymbol{q}) \tag{606}$$

with $D(\boldsymbol{q})$: SSD distortion for choosing transform coefficient level vector $\boldsymbol{q}$
$R(\boldsymbol{q})$: Number of bits required for representing $\boldsymbol{q}$

$\Longrightarrow$ Rate-distortion optimized quantization (as considered for run-level coding)

- **Mode decision**: Select coding mode c for a macroblock or block

$$c^* = \arg\min_{c} \; D(c) + \lambda \cdot R(c) \tag{607}$$

with $D(c)$: SSD distortion for choosing coding mode c for the block
$R(c)$: Number of bits for block when coded with mode c

$\Longrightarrow$ Can be applied for selecting intra prediction mode

- **Motion search**: Will be considered later in lecture

Comparison of H.263 and MPEG-4 Visual with MPEG-2 Video

Comparison of coding efficiency for intra-picture coding

- Selection of all features that contribute to coding efficiency
  - H.262 | MPEG-2 Video conforming to Main profile
  - H.263+ with advanced intra coding, deblocking filter, modified quantization
  - MPEG-4 Visual with MPEG-style quantization

- Apply same level of encoder optimization for fair comparison
  - Best possible coding efficiency for given syntax
  - Ignore constraints such as real-time operation

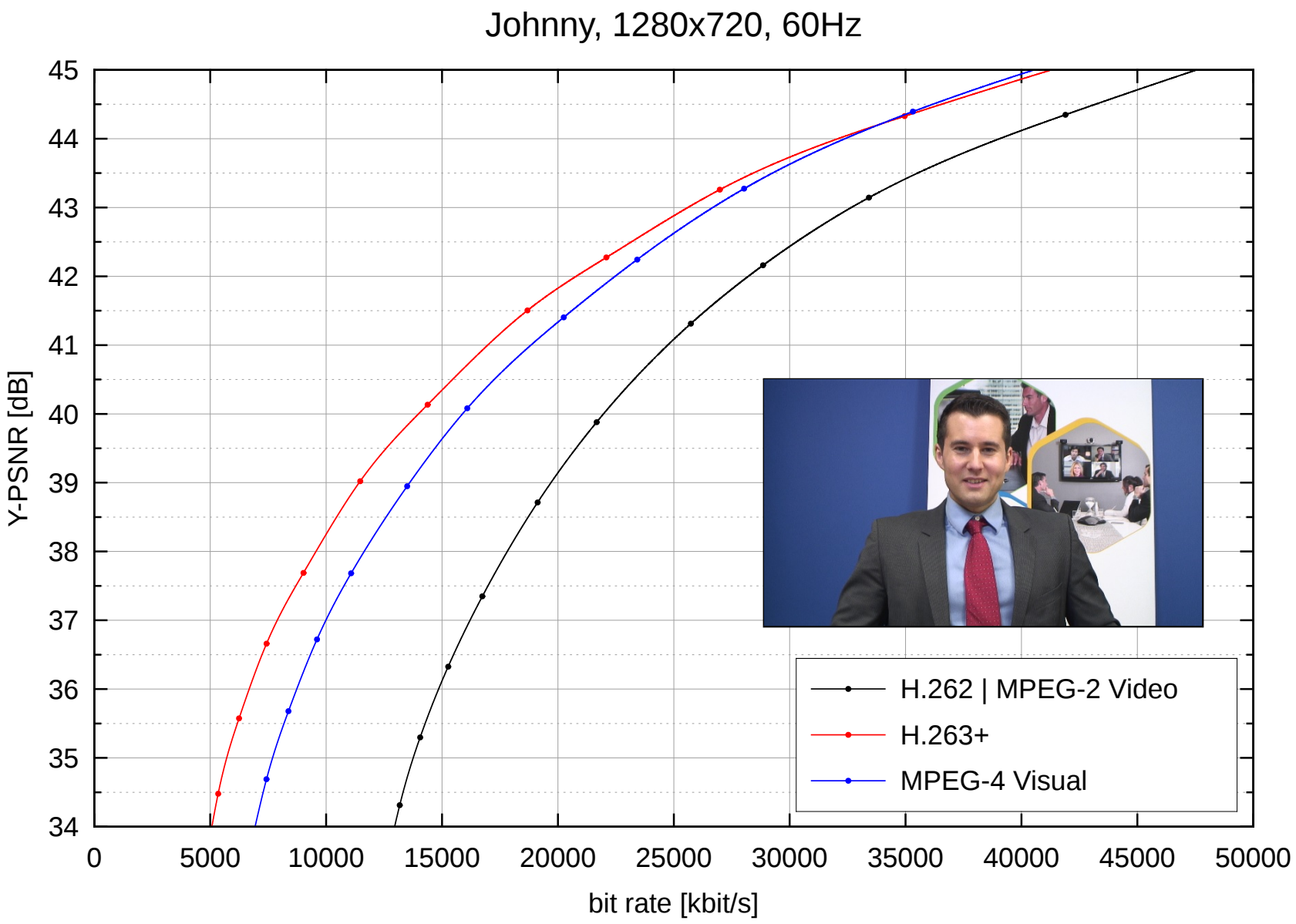
  $\Longrightarrow$ Use rate-distortion optimized quantization for all standards

  $\Longrightarrow$ Apply rate-distortion optimized mode decision where applicable

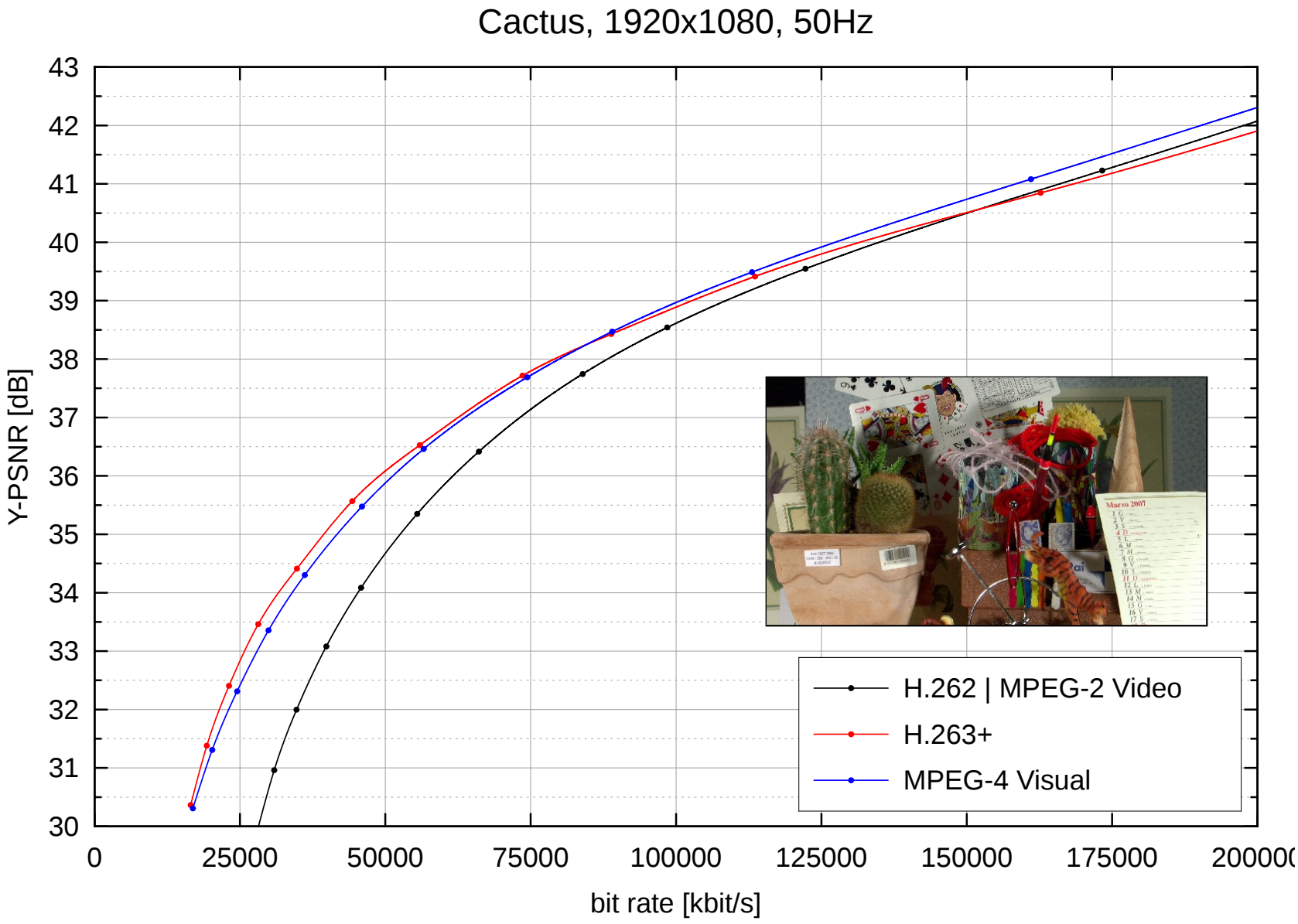
- General coding conditions
  - Encode 10 pictures of 12 video sequences (6 in 720p, 6 in 1080p)
  - Flat quantization matrices (quality is measured using PSNR)
  - Same quantization parameter for all macroblocks
  - Select Lagrangian parameter according to

$$\lambda = \text{const} \cdot \Delta^2 \qquad \text{(with experimentally determined factor)} \qquad (608)$$

Intra Coding Comparison – Sequence "Johnny"



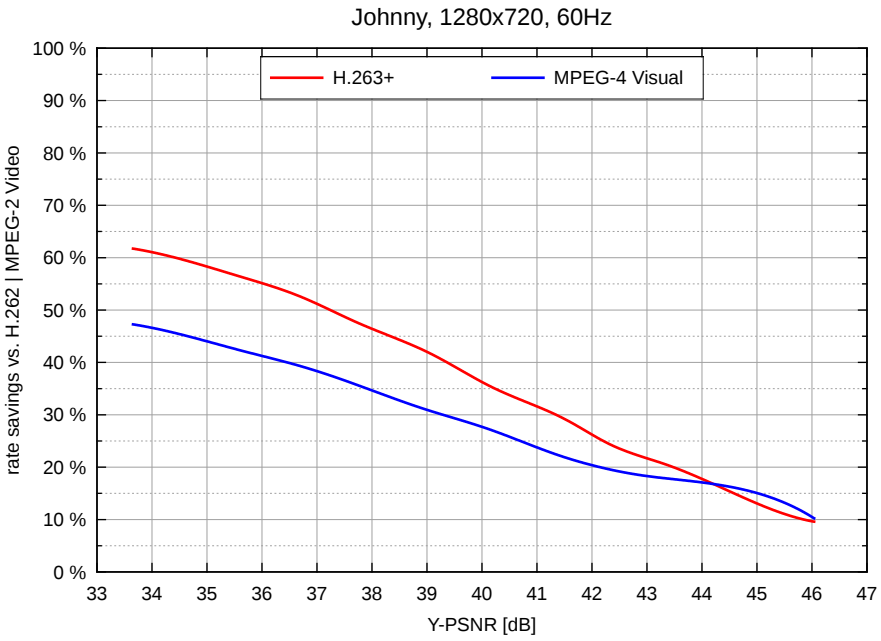
Intra Coding Comparison – Sequence "Cactus"

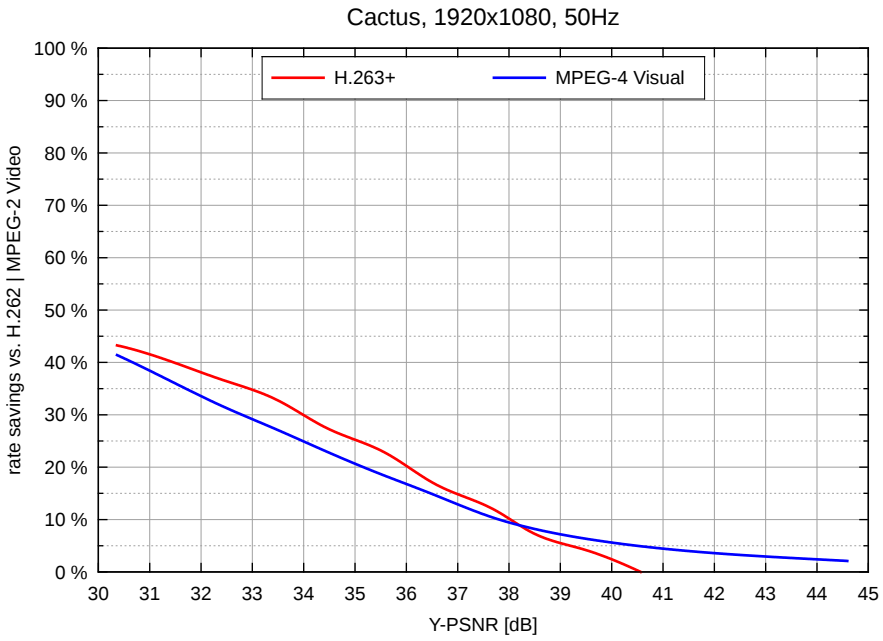


Intra Coding Comparison – Summary

Bit-rate savings of H.263 and MPEG-4 Visual versus H.262 | MPEG-2 Video

- Bit-rate saving at a PSNR value is obtained by interpolating the r-d curves
- Average bit-rate savings are obtained by averaging the savings for 100 PSNR values
- Average bit-rate saving for all sequences
  - H.263+ versus H.262 | MPEG-2 Video: 29%
  - MPEG-4 Visual versus H.262 | MPEG-2 Video: 25%
- Highest savings are obtained for low bit rates





Summary of Intra-Picture Coding in H.263 and MPEG-2 Visual

Intra-picture coding in H.263+

- Transform coding using 8×8 DCT
- Prediction of DC and, partly, AC coefficients
- Coded block pattern
- Adaptive scanning of transform coefficient levels
- Scalar quantization
- Run-level-last coding of transform coefficient levels
- Optional deblocking filter

Intra-picture coding in MPEG-4 Visual

- Similar tools as in advanced intra coding mode of H.263+ (Annex I)
- Additionally includes quantization weighting matrices

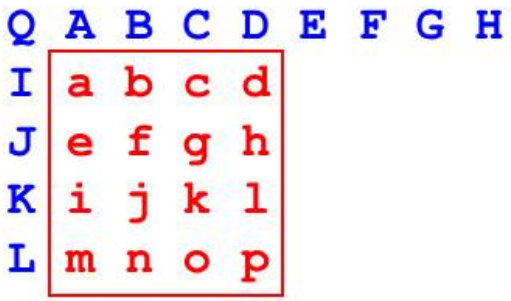
Rate-distortion optimized encoder control

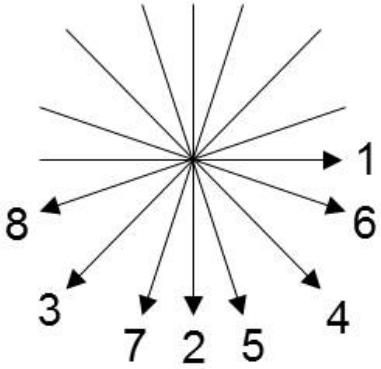
- Split overall optimization problem into smaller problems
- Encoder decision by minimizing $D + \lambda \cdot R$

$\Rightarrow$ Rate-distortion optimized quantization (RDOQ)

$\Rightarrow$ Rate-distortion optimized mode decision

Intra-Picture Coding in H.264 | MPEG-4 AVC





H.264 | MPEG-4 AVC – Overview

ITU-T Rec. H.264 | ISO/IEC 14496-10 (MPEG-4 Advanced Video Coding)

- Video coding standard jointly developed by ITU-T VCEG and ISO/IEC MPEG
- Widely used today in many application spaces
  - Digital television, blu-ray optical disc, digital cameras, mobile phones, video streaming, video conferencing
  - Supported in more than 1 billion devices
  - Every second bit in the Internet is part of a H.264 | MPEG-4 AVC bitstream
- Version 1 (2003):
  - Three profiles: Baseline, Main, Extended (4:2:0, 8 bit)
- Fidelity range extensions (2005)
  - Improvements for large picture sizes, other chroma formats, higher bit depth
  - High, High 10, High 4:2:2, High 4:4:4 profiles (removed later)
  - Later: Addition of High 4:4:4 Predictive and intra-only profiles
- Scalable video coding extension (2007)
  - Extension for scalable video coding (SVC)
- Multiview video coding extension (2009)
  - Extension for multiview video (MVC)
  - Used for 3d-blu-ray discs

Intra-Picture Coding in H.264 | MPEG-4 AVC

Main features of intra-picture coding

- Spatial intra prediction with multiple prediction modes
- Transform coding with 4×4 integer transform
- Optional 8×8 integer transform (High profile)
- Scalar quantization
- Two entropy coding methods:
  - Context-adaptive variable length coding (CAVLC)
  - Context-adaptive binary arithmetic coding (CABAC) – Main/High profile
- Deblocking filter (conceptually similar to Annex J of H.263)

Picture partitioning and intra coding modes

- Pictures are partitioned into 16×16 macroblocks
- 4 intra coding modes are supported (selection on MB level)
  - Intra-4×4
  - Intra-8×8 (High profile)
  - Intra-16×16
  - Intra-PCM (direct coding of samples)

Coding of Intra-4×4 macroblocks

Spatial prediction of blocks

- DC, horizontal, vertical prediction of transform coefficients (as in H.263, MPEG-4 Visual) can similarly also be realized in spatial domain
- Prediction in spatial domain offers more possibilities

Coding of luma component

- 16×16 luma block is partitioned into 16 4×4 blocks
- 4×4 blocks are spatially predicted
- 9 intra prediction modes are supported
- Prediction error of 4×4 blocks is transform-coded

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

Coding of chroma components

- Both 8×8 chroma blocks are spatially predicted
- 4 intra prediction modes are supported
- Prediction error is coded using transform coding
- 4×4 transform and second level transform of DCs

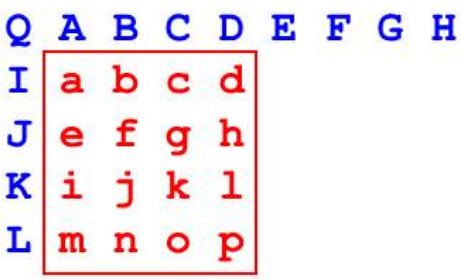
18	19
20	21

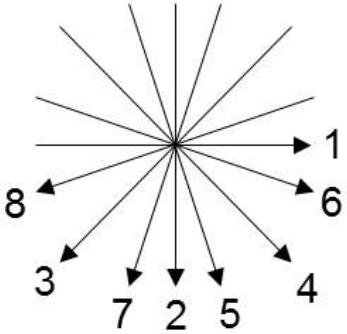
22	23
24	25

Spatial Intra Prediction for 4×4 Blocks

Spatial intra prediction

- Predict block using already coded neighboring samples
- DC prediction (mean value) and 8 directional prediction modes





Coding order and boundary conditions

- Blocks are coded in z-scan order
- Samples used for prediction have to be "available" (already reconstructed)
- Not all modes are available for all blocks
- Samples "E", "F", "G" and "H" can be replaced with sample "D"

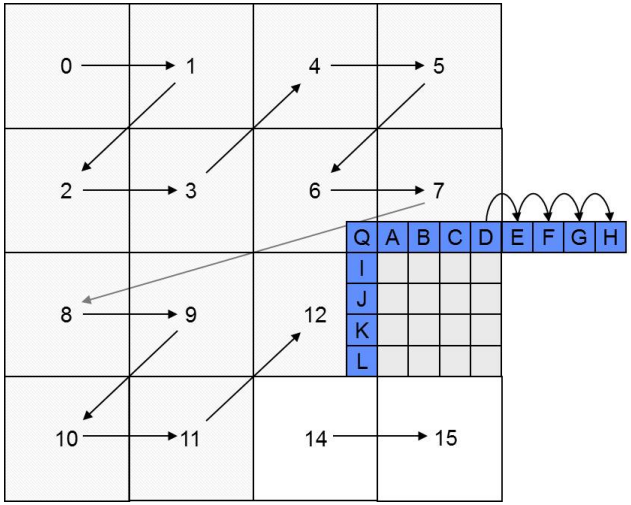
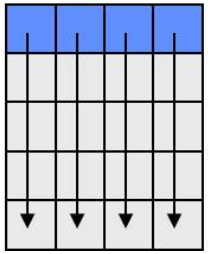
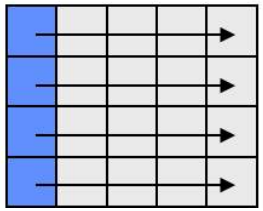


Illustration of Intra Prediction Modes

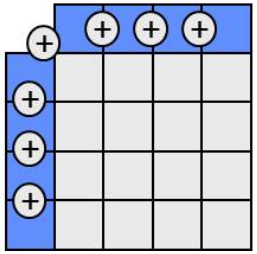
Mode 0 - Vertical



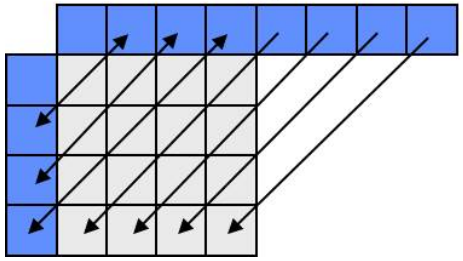
Mode 1 - Horizontal



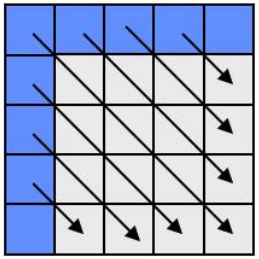
Mode 2 - DC



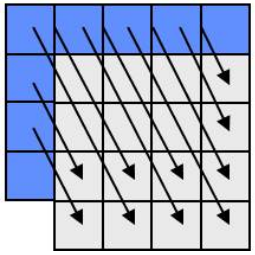
Mode 3 – Diagonal Down/Left



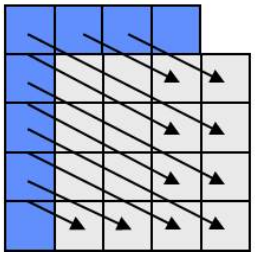
Mode 4 – Diagonal Down/Right



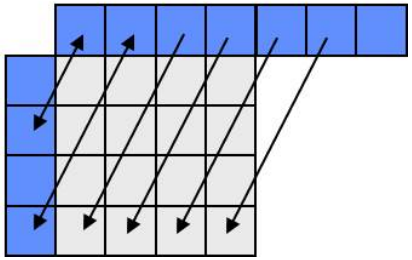
Mode 5 – Vertical-Right



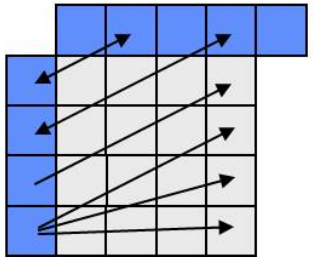
Mode 6 – Horizontal-Down



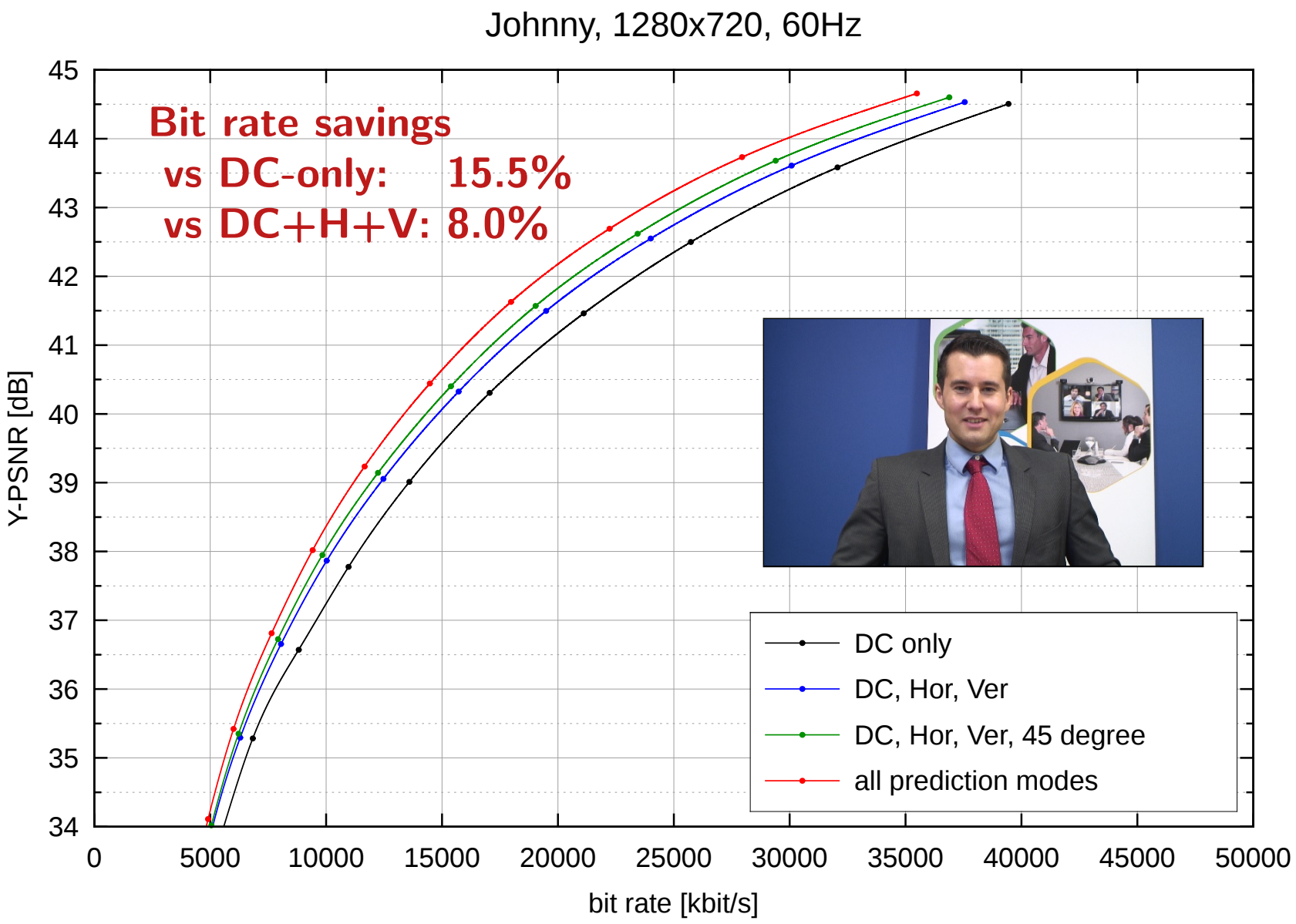
Mode 7 – Vertical-Left



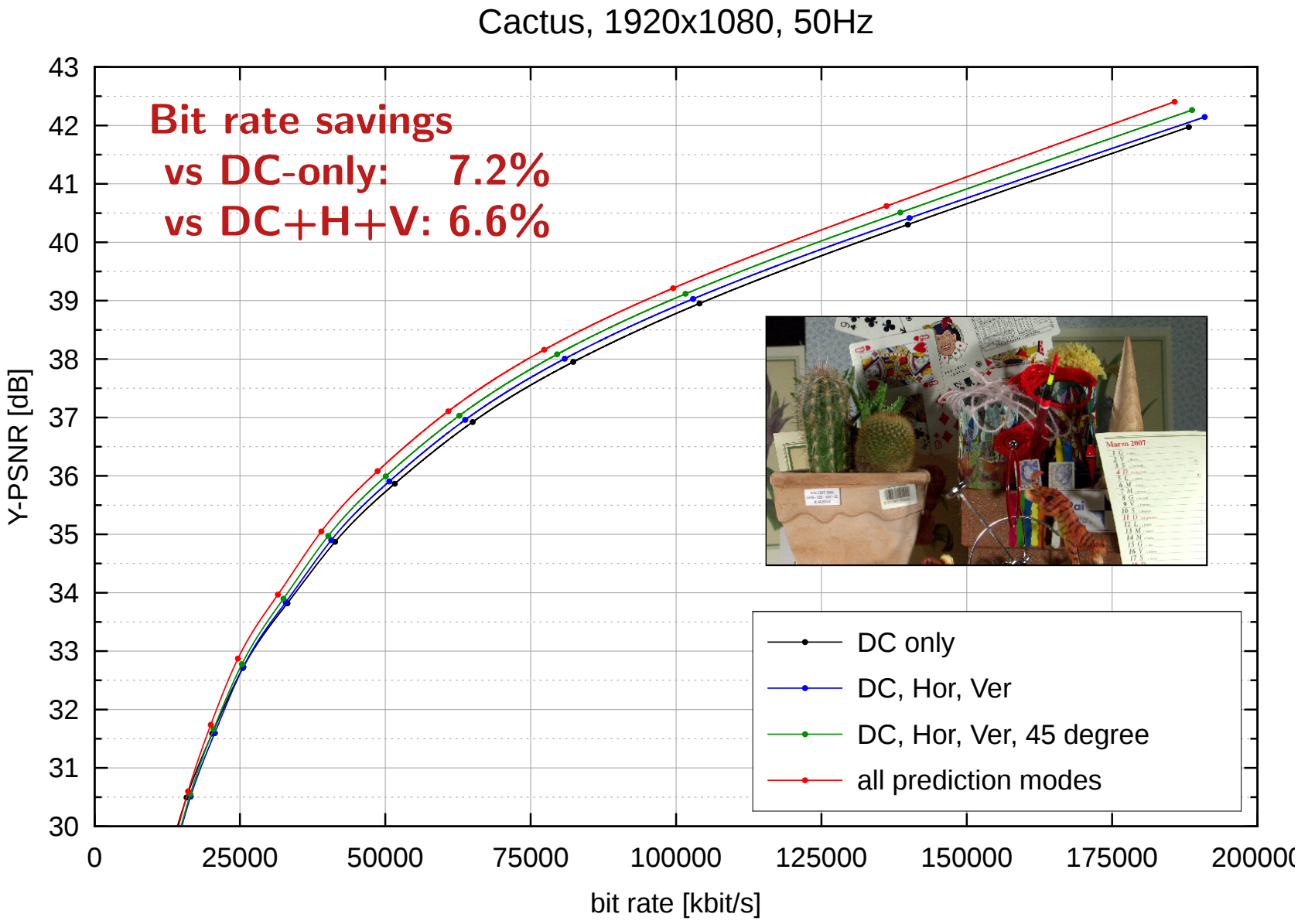
Mode 8 – Horizontal-Up



Efficiency of Intra Prediction – Sequence "Johnny"



Efficiency of Intra Prediction – Sequence "Cactus"



Transform Coding of 4×4 Blocks

Separable 4×4 integer transform

- Orthogonal block transform with integer approximation of DCT

$$\boldsymbol{u}_{4\times4} = \boldsymbol{A}_{4\times4} \cdot \boldsymbol{s}_{4\times4} \cdot \boldsymbol{A}_{4\times4}^{\mathrm{T}} \qquad \text{with} \qquad \boldsymbol{A}_{4\times4} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 2 & 1 & -1 & -2 \\ 1 & -1 & -1 & 1 \\ 1 & -2 & 2 & -1 \end{bmatrix} \tag{609}$$

- Inverse is specified by exact integer operations
  $\Longrightarrow$ No accumulation of transform mismatches
- Easy implementation (only additions and bit shift operations)
- Basis vectors have different norms
  $\Longrightarrow$ Compensated by modifying the quantizer step size accordingly

Scalar quantization of transform coefficients

- Uniformly distributed reconstruction levels
- Logarithmic quantization step size control ($\Delta \approx \alpha \cdot 2^{\mathrm{QP}/6}$)
- Smaller quantization step sizes for chroma (as in Annex T of H.263)
- Support for quantization weighting matrices (High profile)
- Quantization parameter can change at macroblock level

Coding of Transform Coefficient Levels

Context-adaptive variable length coding (CAVLC)

- Coded block pattern (for all six 8×8 block) using VLC table
- Zig-zag scan for mapping matrix into vector
- Syntax element "coeff_token" for 4×4 blocks
  - Specifies number of non-zero coefficients and number of trailing ones
  - Chosen VLC table depends on number of non-zero coefficients in already coded neighboring blocks
- Additionally code "runs" and "levels" as well as signs for trailing ones

Context-adaptive binary arithmetic coding (CABAC) [Main, High profile]

- Binary arithmetic coding of all low-level syntax elements
- Coded block pattern (flag for each of the six 8×8 blocks)
- Flag for 4×4 blocks indicating whether non-zero levels are present
- Coding of a significance map
  - "significance_flag" indicating whether level is non-zero
  - if non-zero, "last_flag" indicating whether last non-zero level
- Coding of absolute levels (minus 1) and signs
- Probability models are adapted to statistics during encoding and decoding

Intra-16×16 and Intra-8×8 Macroblocks

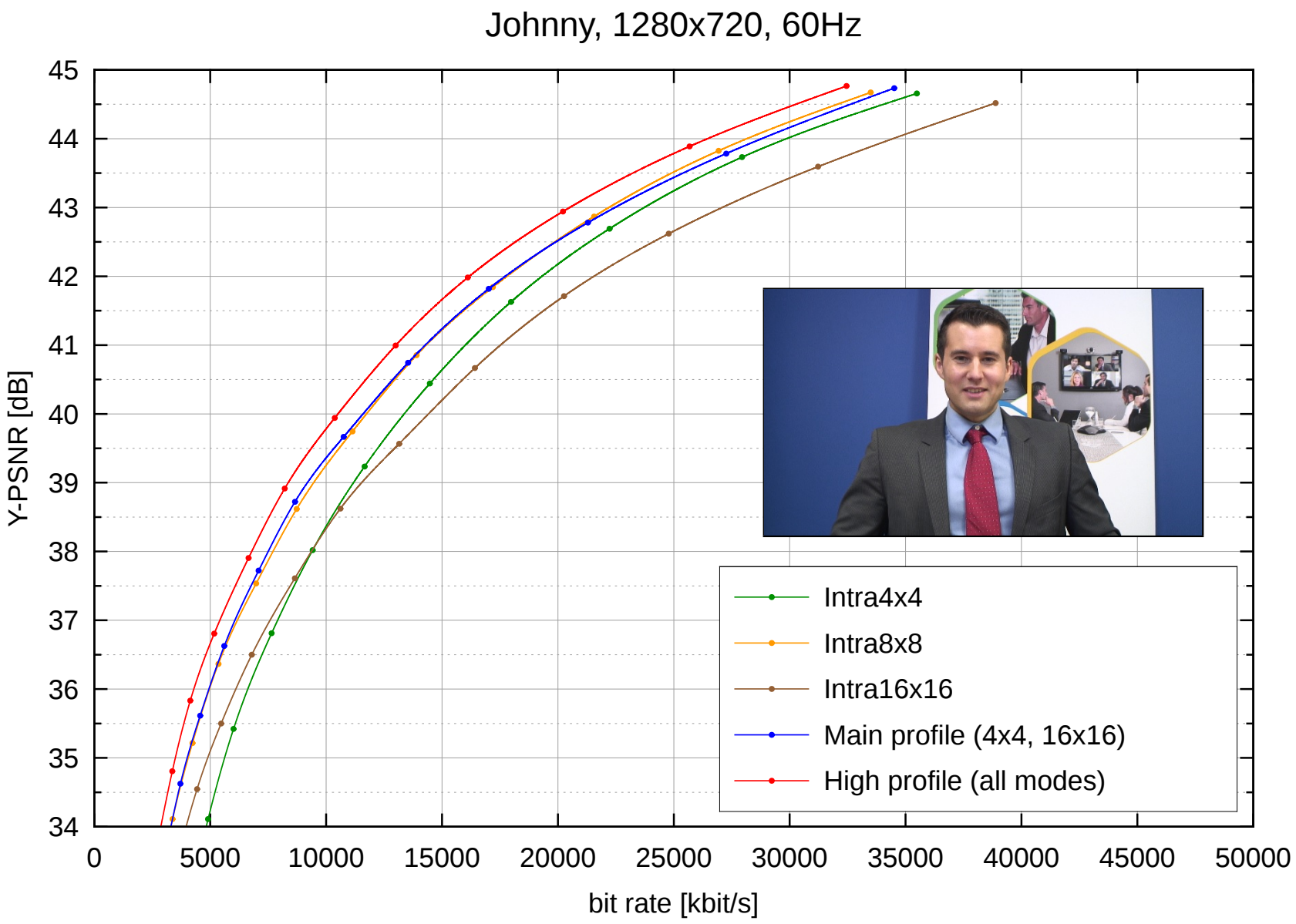
Intra-16×16 macroblock mode

- Prediction of 16×16 luma block
- Four prediction modes: DC, horizontal, vertical, planar
- 4×4 transform of all sixteen 4×4 blocks
- Additional 4×4 Hadamard transform of DC coefficients
- DC block is treated separately in entropy coding
- Similar concept with 2×2 Hadamard transform of DC coefficients is also used for chroma blocks (for all intra coding modes)

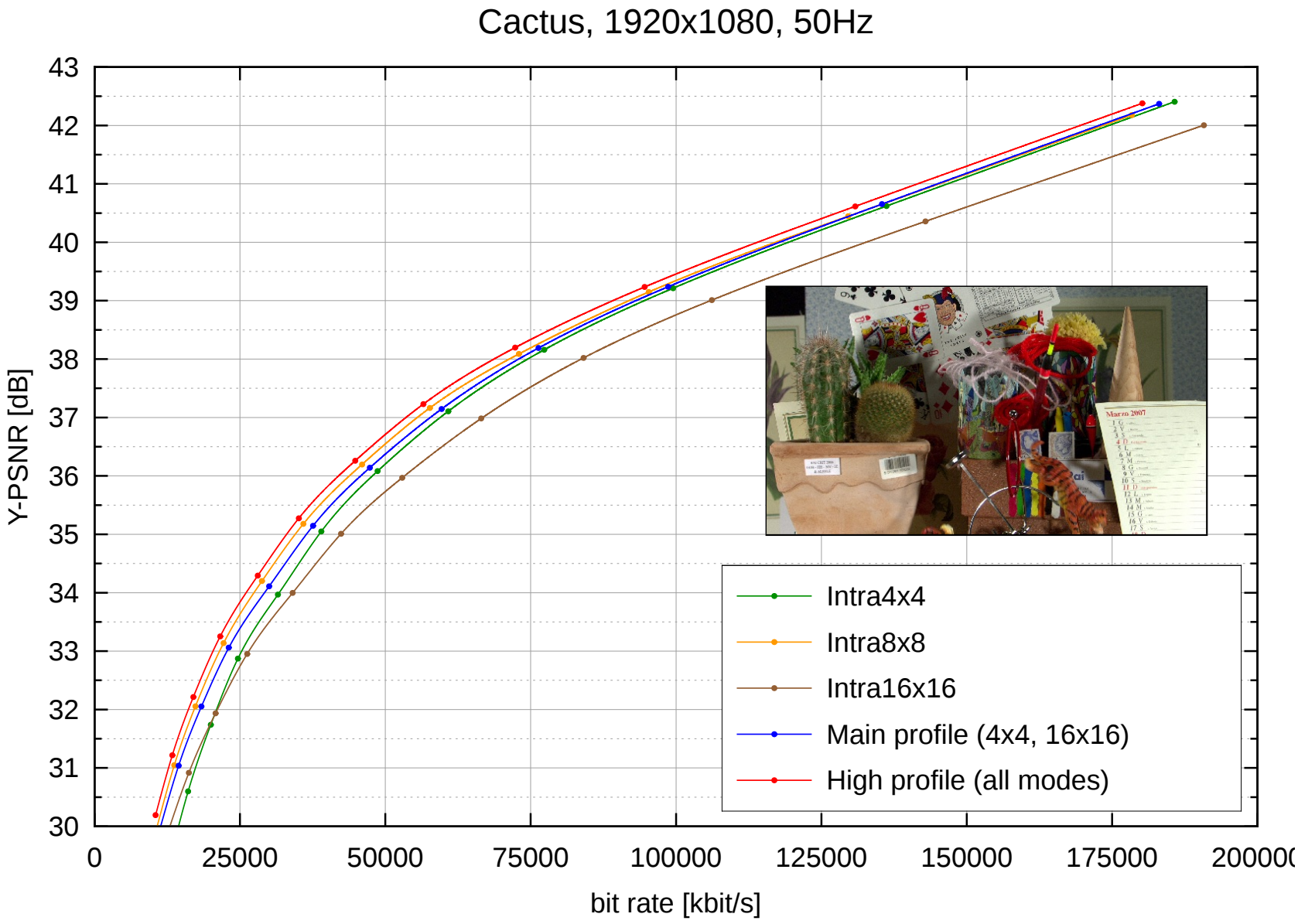
Intra-8×8 macroblock mode (High profile)

- Prediction of 8×8 blocks of luma component
- Same prediction modes as for Intra-4×4 (but extended to larger block size)
- Reference samples are low-pass filtered before they are used for prediction
- 8×8 integer transform for the four luma sub-blocks
- Entropy coding is extended to 8×8 transform blocks

Coding Efficiency of Intra Modes – Sequence "Johnny"



Coding Efficiency of Intra Modes – Sequence "Cactus"



Coding Efficiency Comparison with Older Standards

Comparison of coding efficiency for intra-picture coding

- Selection of all features that contribute to coding efficiency
  - H.262 | MPEG-2 Video conforming to Main profile
  - H.263+ with advanced intra coding, deblocking filter, modified quantization
  - MPEG-4 Visual with MPEG-style quantization
  - **H.264 | MPEG-4 AVC High profile with CABAC**

- Apply same level of encoder optimization for fair comparison
  - Best possible coding efficiency for given syntax
  - Ignore constraints such as real-time operation

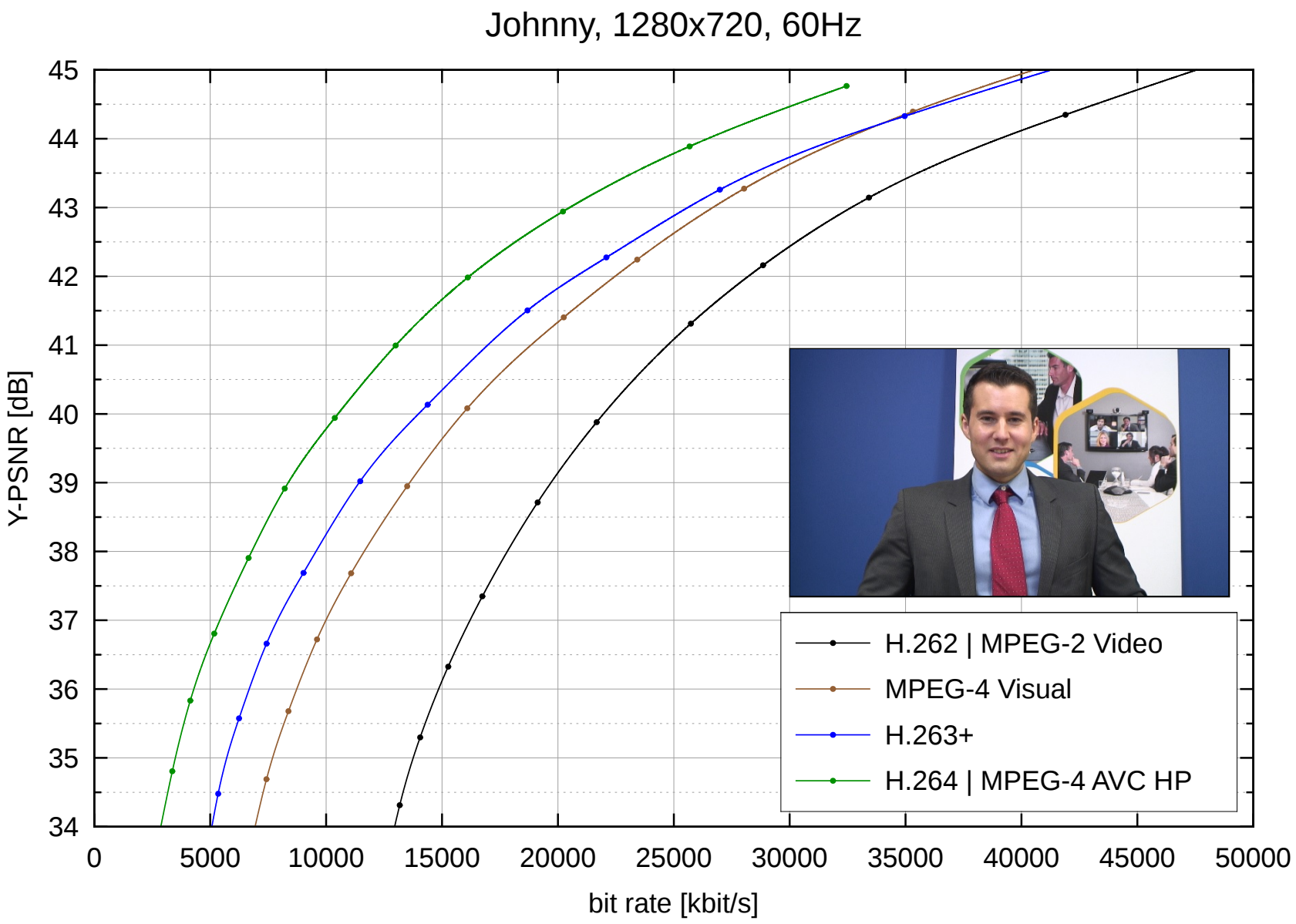
  $\Longrightarrow$ Use rate-distortion optimized quantization for all standards

  $\Longrightarrow$ Apply rate-distortion optimized mode decision where applicable

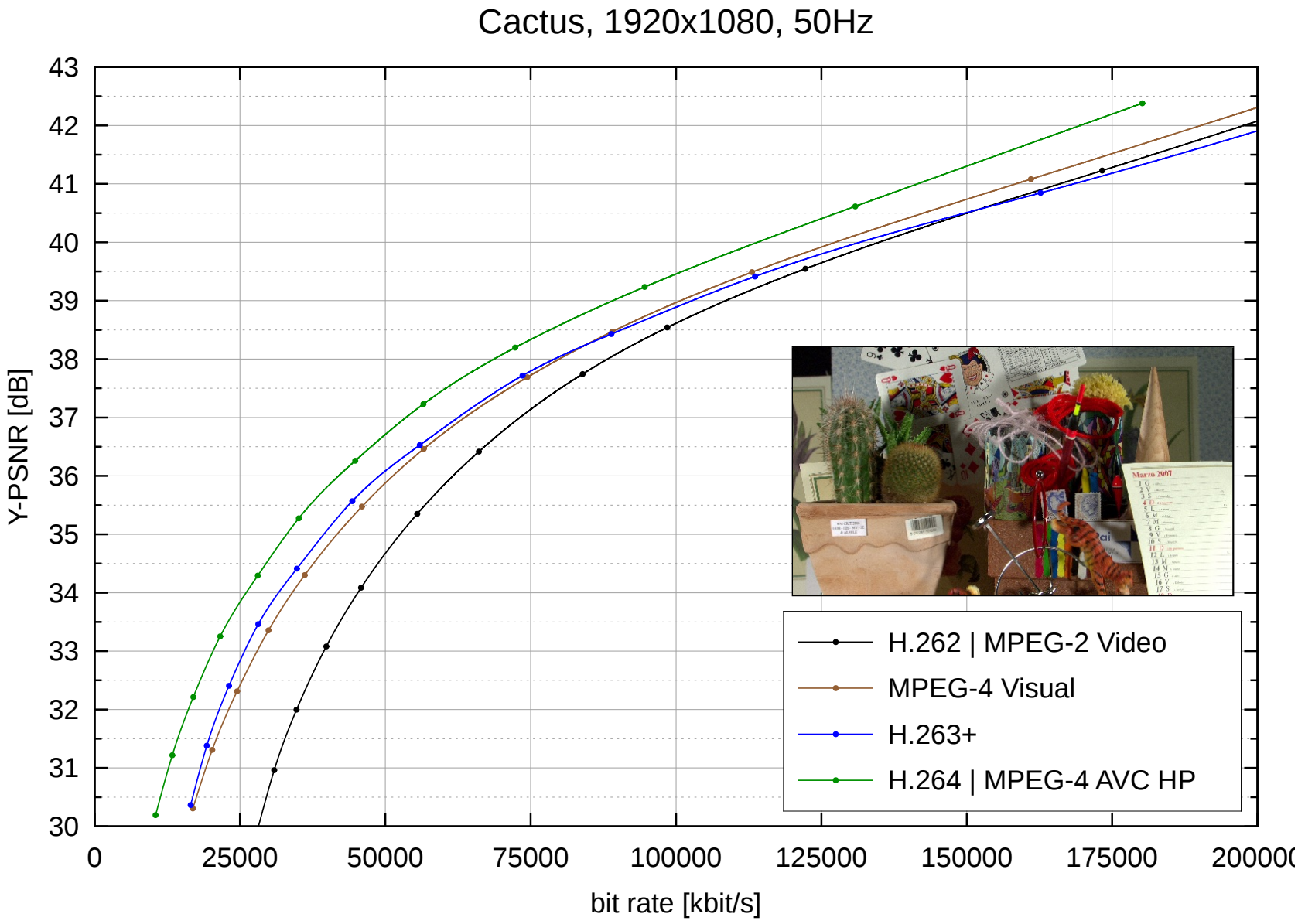
- General coding conditions
  - Encode 10 pictures of 12 video sequences (6 in 720p, 6 in 1080p)
  - Flat quantization matrices (quality is measured using PSNR)
  - Same quantization parameter for all macroblocks
  - Select Lagrangian parameter according to

$$\lambda = \text{const} \cdot \Delta^2 \qquad \text{(with experimentally determined factor)} \qquad (610)$$

Intra Coding Comparison – Sequence "Johnny"



Intra Coding Comparison – Sequence "Cactus"



Intra Coding Comparison – Summary

Bit-rate savings of H.264 | MPEG-4 AVC versus older video coding standards

- Bit-rate saving at a PSNR value is obtained by interpolating the r-d curves
- Average bit-rate savings are obtained by averaging the savings for 100 PSNR values
- Highest savings are obtained for low bit rates
- Average bit-rate saving for all sequences are summarized below

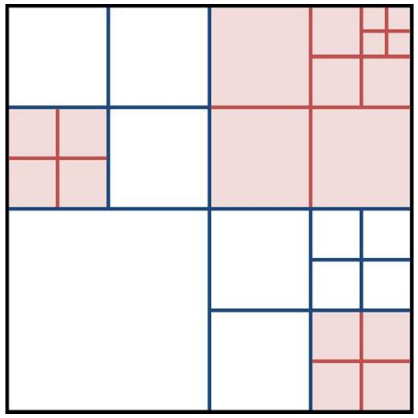
codec	average bit rate savings relative to ...		
	H.263+	MPEG-4	MPEG-2
H.264 / AVC	21.1 %	28.2 %	45.6 %
H.263+		9.7 %	32.5 %
MPEG-4			26.3 %

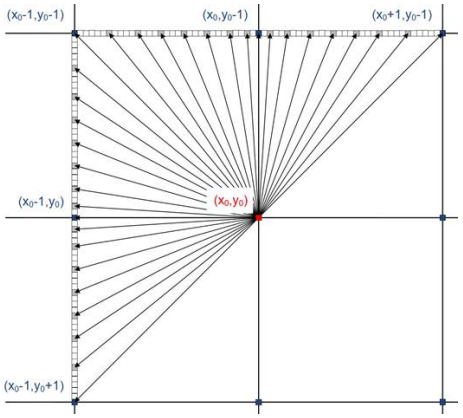
Summary of Intra-Picture Coding in H.264 | MPEG-4 AVC

Intra-picture coding in H.264 | MPEG-4 AVC

- Four intra macroblock modes
  - Intra-4×4, Intra-8×8, Intra-16×16: Prediction & transform coding
  - Intra-PCM: Direct coding of samples
- Intra prediction in spatial domain using neighboring samples
  - Intra-4×4 and Intra-8×8: Eight directional modes & DC prediction
  - Intra-16×16 and chroma: Four intra prediction modes
- Transform: Integer approximation of DCT
  - Intra-4×4: Transform of 4×4 blocks
  - Intra-8×8: Transform of 8×8 blocks
  - Intra-16×16 and chroma: Transform of 4×4 blocks + DC transform
- Scalar quantization
  - Uniform reconstruction quantizer (with optional weighting matrices)
  - Norms of basis vectors are taken into account in quantization
- Two methods for entropy coding
  - Context-adaptive variable length coding (CAVLC)
  - Context-adaptive binary arithmetic coding (CABAC)
- Deblocking filter

Intra-Picture Coding in H.265 | MPEG-H HEVC





H.265 | MPEG-H HEVC – Overview

ITU-T Rec. H.265 | ISO/IEC 23008-2 (MPEG-H High Efficiency Video Coding)

- Jointly developed by ITU-T VCEG and ISO/IEC MPEG
- Last video coding standard with focus on coding of high-resolution video
- Significantly increased coding efficiency, particularly for high-resolution video
- First version was finalized in January 2013
- First version specifies three profiles
  - Main profile (4:2:0 chroma format, 8 bit per sample)
  - Main 10 profile (4:2:0 chroma format, 10 bit per sample)
  - Main Still Picture profile (intra-only coding subset of Main profile)
- Extensions are under development
  - Fidelity range extension (other chroma samplings, higher bit depth)
  - Scalable video coding extension
  - Multiview video coding extension
  - Multiview video plus depth coding extension

Main Features of H.265 | MPEG-H HEVC

Main improvements relative to H.264 | MPEG-4 AVC

- Larger block sizes for transform coding and motion compensation
- Increased flexibility for partitioning a picture into blocks
- Improved interpolation filters and motion vector coding
- Increased number of intra prediction modes
- Improved coding of transform coefficient levels
- Additional in-loop filter: Sample-adaptive offset filter

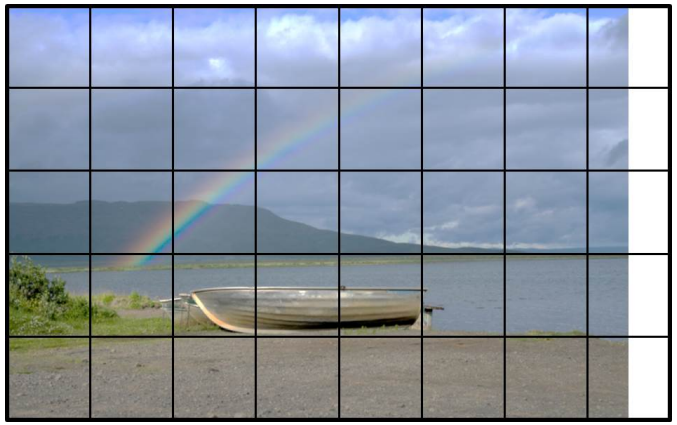
Intra-Picture Coding in H.265 | MPEG-H HEVC

- Spatial intra prediction and transform coding of prediction residual
- Increased number of intra prediction modes compared to H.264/AVC
- Larger transform sizes
- More flexible partitioning of a picture
- Improved coding of transform coefficient levels (for larger blocks)
- Deblocking filter and additional sample-adaptive offset filter

Picture Partitioning in H.265 | MPEG-H HEVC

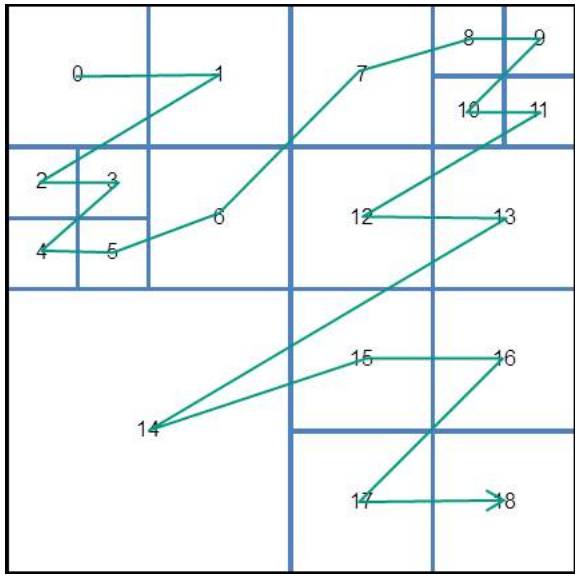
Picture partitioning into **coding tree blocks**

- Coding tree blocks (CTBs): Fixed size of 16×16, 32×32 or 64×64 luma samples
- Size of CTBs chosen by encoder
- Luma and chroma CTBs together with syntax are called **coding tree unit** (CTU)



Partitioning of coding tree blocks

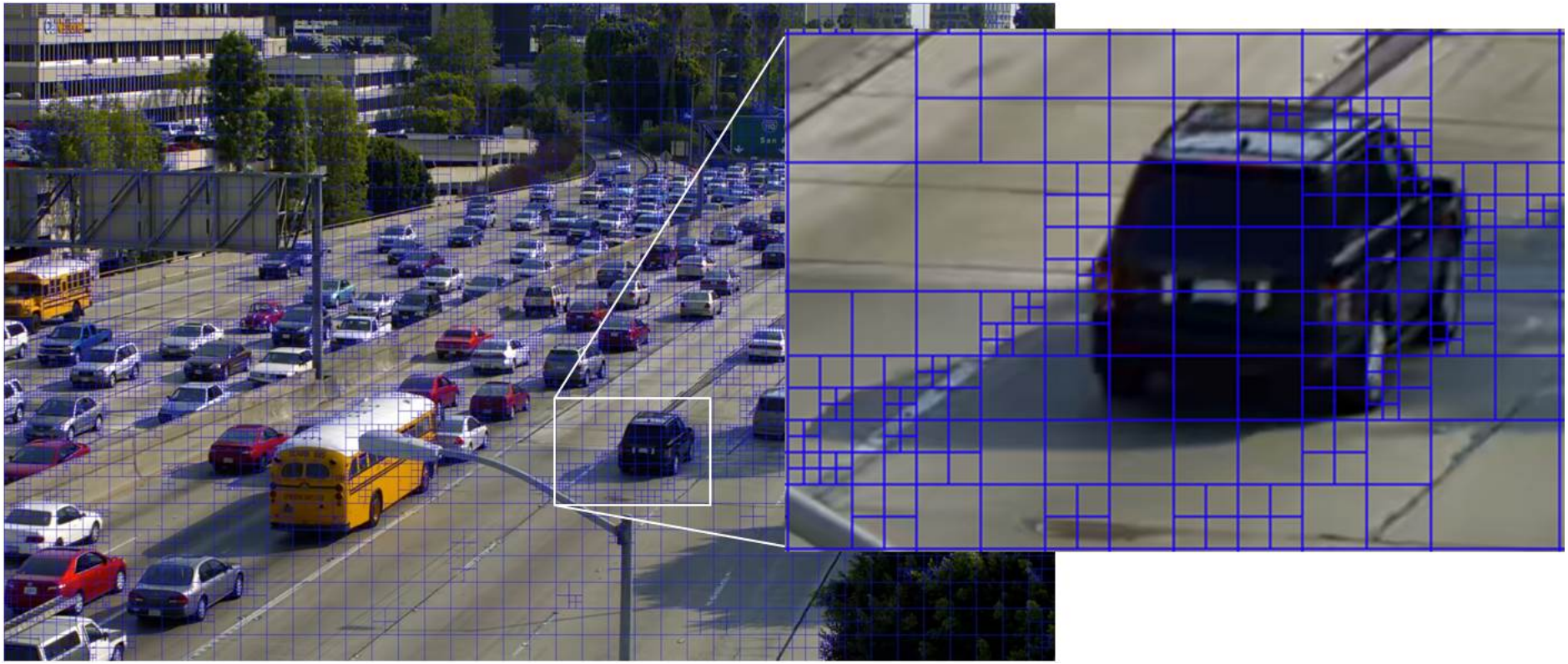
- Quad-tree partitioning into **coding blocks** (CBs)
- Luma and chroma CBs together with syntax are called **coding unit** (CU)
- Maximum CU size: Size of the CTB
- Minimum CU size: Selected by encoder, but equal to or larger than 8×8 luma samples
- Coding mode (intra or inter) is chosen for CU
- CU is similar to macroblock in older standards
- Coding order: Z-scan



Example: Picture Partitioning into Coding Units

Example for picture partitioning into coding units

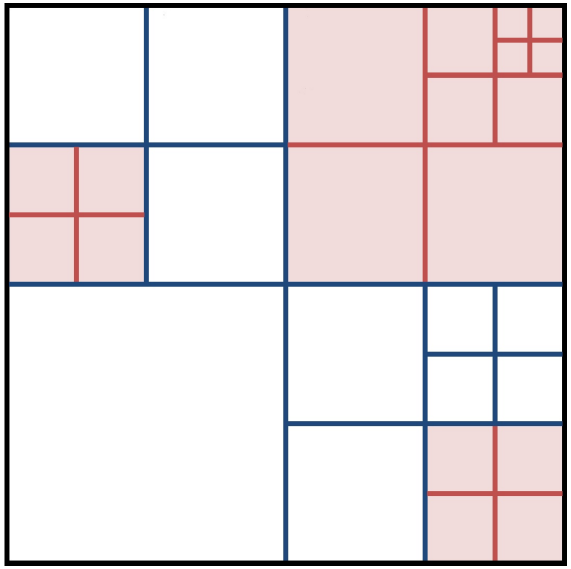
- Picture with 2560×1600 luma samples of HEVC test sequence "Traffic"
- Quadtree-based partitioning into coding unit represents a simple scheme for locally adapting the block sizes to the image structure



Intra Coding of Coding Units in H.265 | MPEG-H HEVC

Partitioning of a CB into **transform blocks** (TBs)

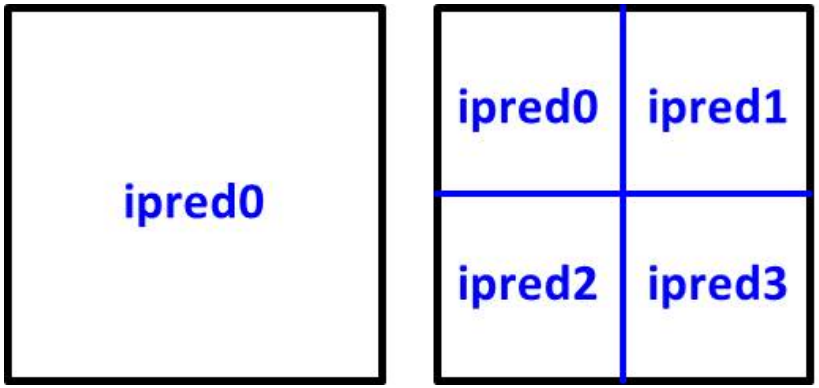
- Nested quad-tree partitioning
- TB corresponds to a single block transform
- Min. and max. TB size are selected by encoder
- Supported transforms: 4×4, 8×8, 16×16, 32×32
- Luma and chroma TBs together with syntax form a **transform unit** (TU)
- Special case: Chroma 4×4 blocks are not split



Intra prediction and mode signaling

- One or four luma intra prediction modes per coding unit
- One chroma prediction mode per CU
- Actual intra prediction is performed transform block by transform block

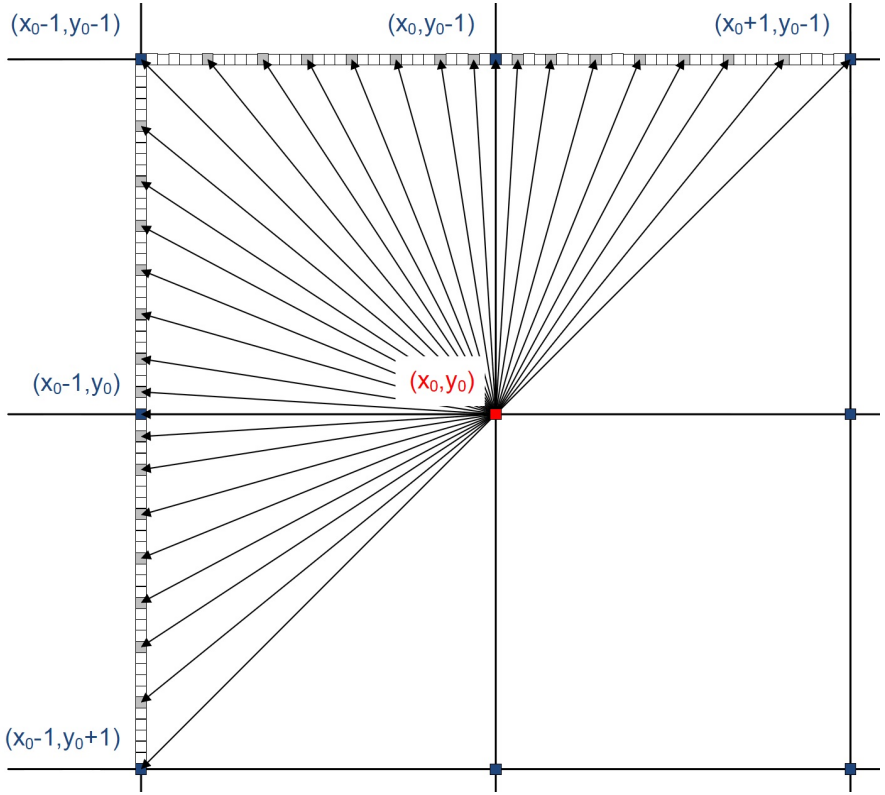
  $\Longrightarrow$ Improved prediction accuracy



Spatial Intra Prediction of Transform Blocks

Prediction of luma transform blocks

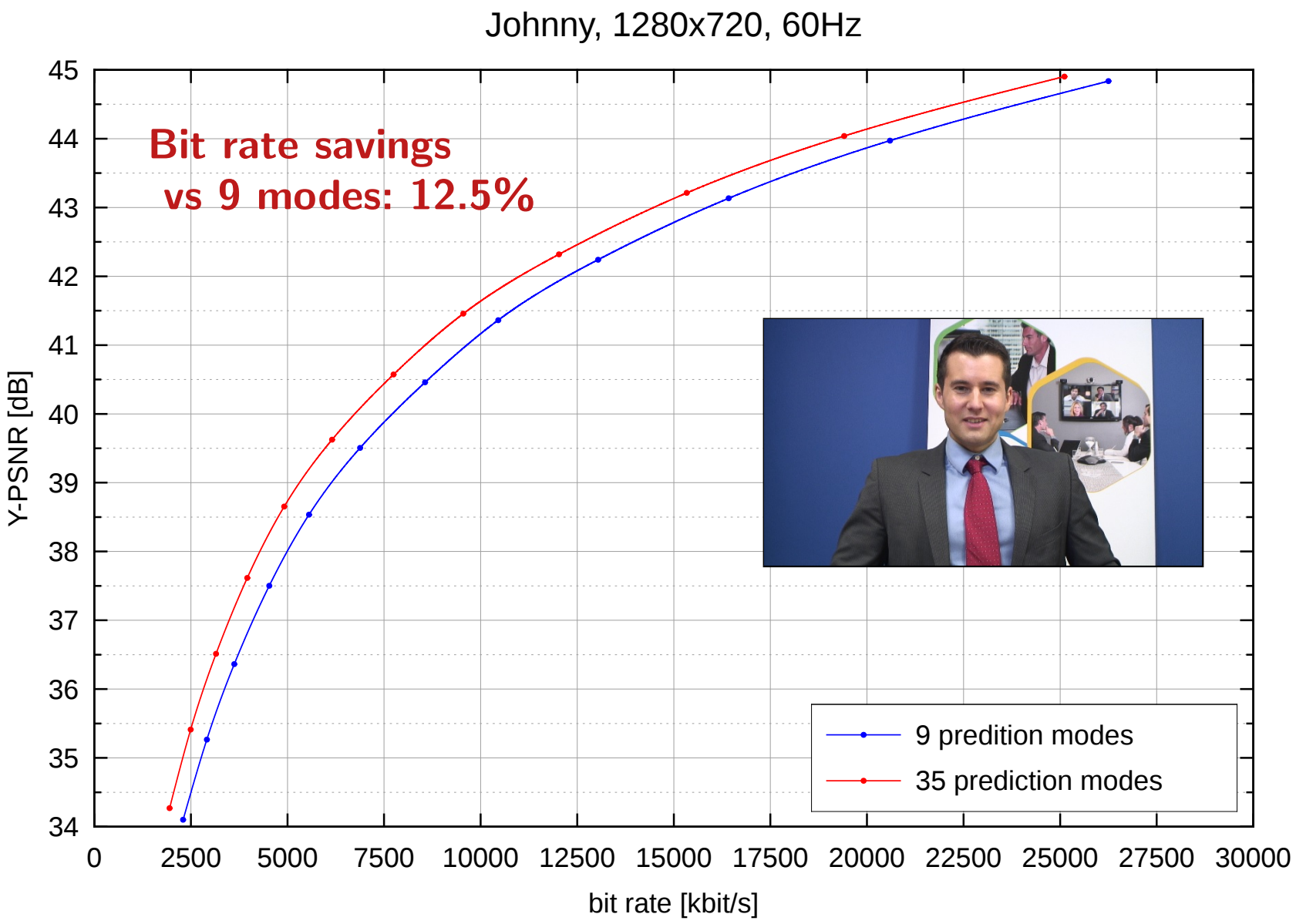
- Spatial intra prediction using neighboring samples of already coded blocks
- 33 directional prediction modes
- Additionally:
  DC and planar prediction
- Reference sample smoothing depending on block size and prediction direction



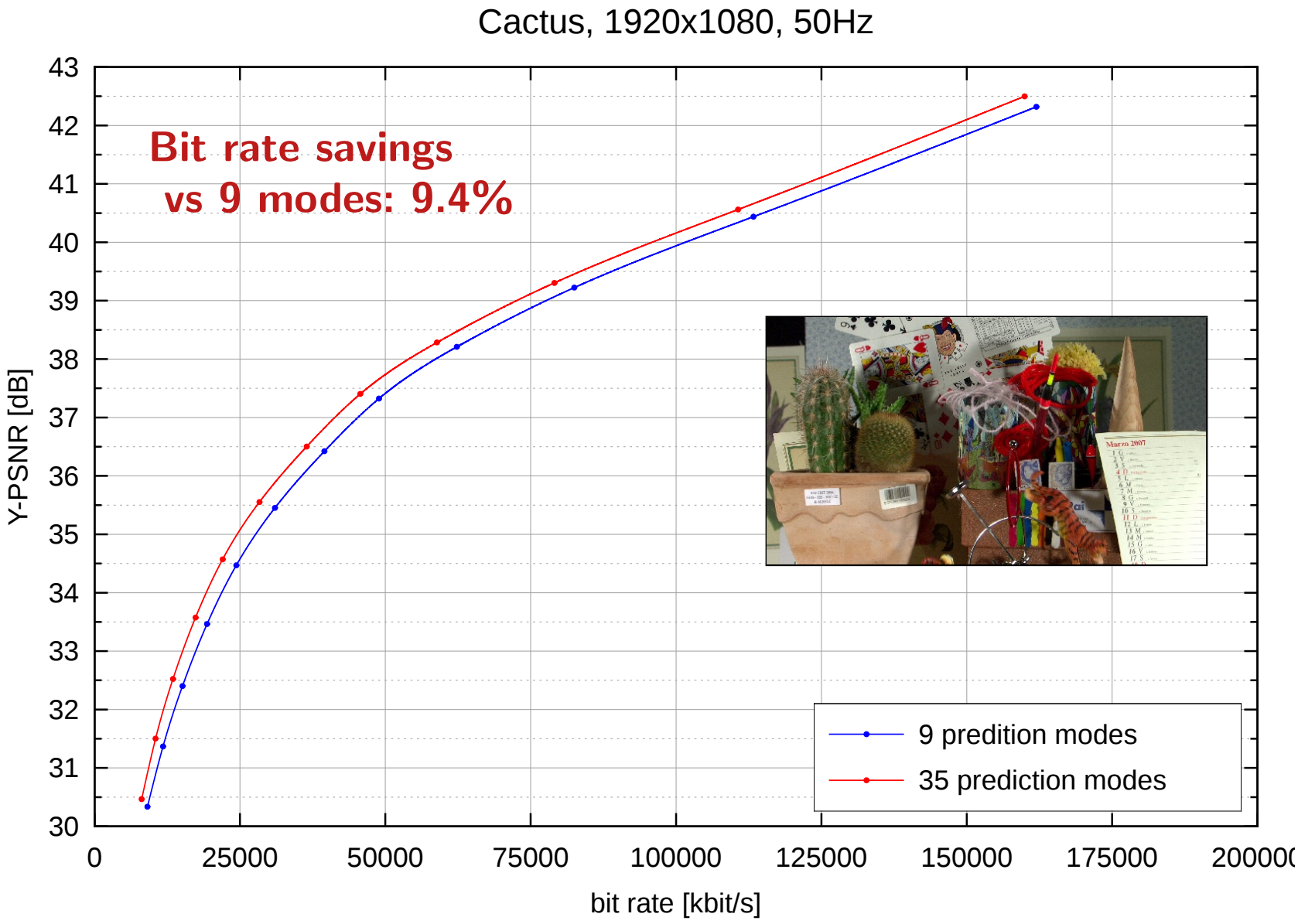
Prediction of chroma transform blocks

- Same prediction mechanism as for luma
- Prediction mode can be selected among the following:
  - Planar, DC, horizontal, vertical prediction mode
  - Same prediction modes as for associated luma block

Number of Intra Prediction Modes – Sequence "Johnny"



Number of Intra Prediction Modes – Sequence "Cactus"



Transform and Quantization in H.265 | MPEG-H HEVC

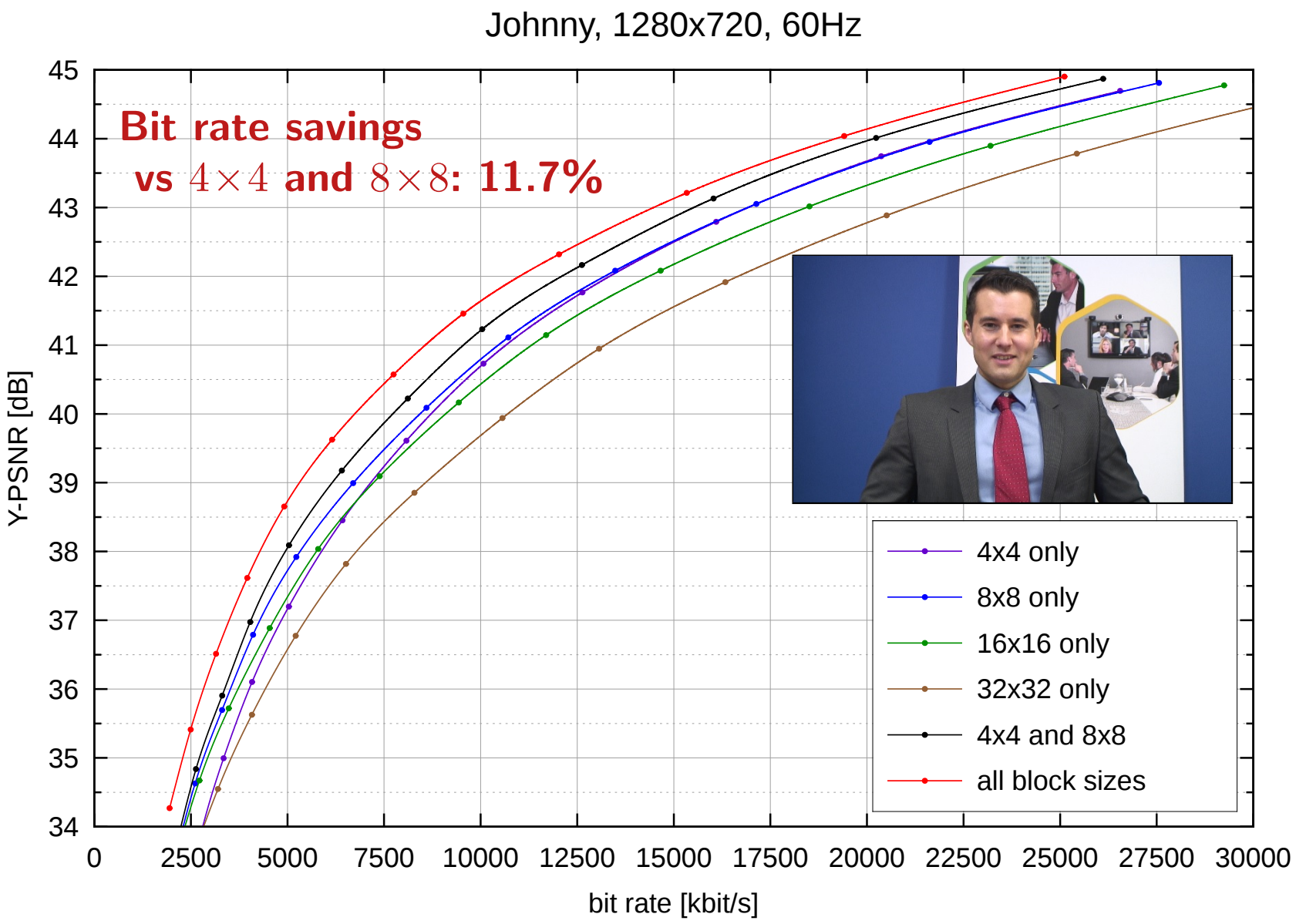
Separable 2-d transform

- 2-d block transform of the size of the transform block
- Separable integer approximation of discrete cosine transform (DCT)
- Basis function have approximately the same norm
- Supported transform sizes: 4×4, 8×8, 16×16, 32×32
- All transform sizes are specified by single 32×32 integer matrix
- Exception: 4×4 luma TBs of intra-picture predicted CUs
  - Separable integer approximation of discrete sine transform (DST)
  - Better fits the statistical properties that the residual amplitudes tend to increase with increasing distance from reference samples

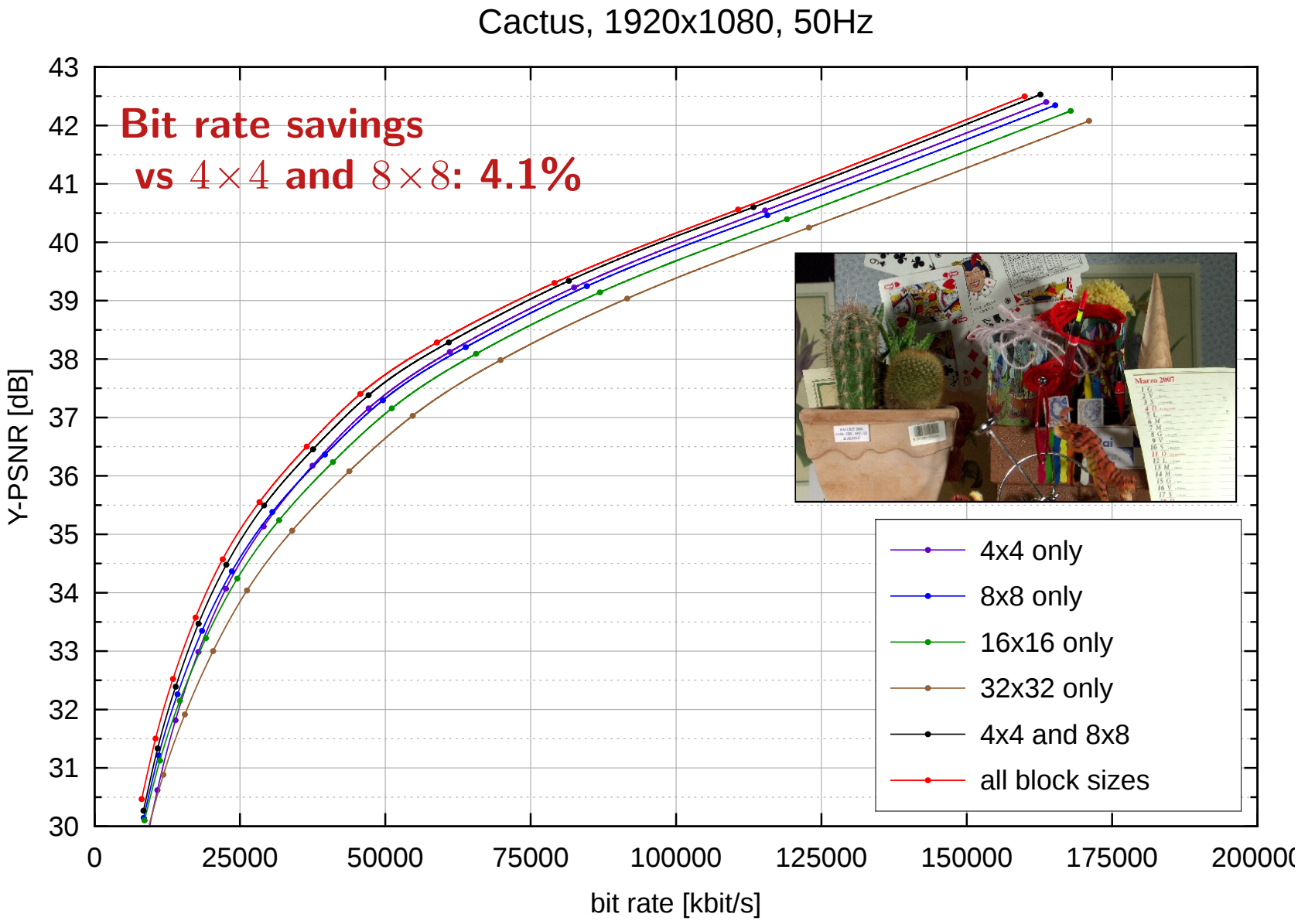
Quantization

- Same uniform reconstruction level quantizer as in H.264 | MPEG-4 AVC
- Quantization step size controlled by quantization parameter (QP)
- Approximately logarithmic mapping between QP and step size
- Quantization scaling matrices are supported

Block Sizes for Prediction and Transform – Sequence "Johnny"



Block Sizes for Prediction and Transform – Sequence "Cactus"



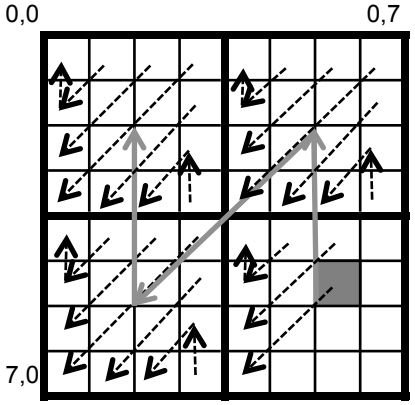
Entropy Coding of Transform Coefficient Levels

Only a single entropy coding method

- Context-adaptive binary arithmetic coding (CABAC)
- Core algorithm of CABAC is unchanged relative to H.264 | MPEG-4 AVC

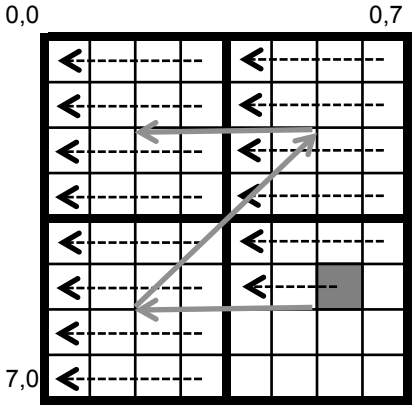
Coding of transform coefficient levels

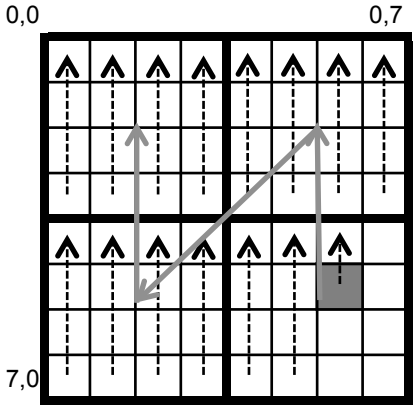
- Coded block flag for transform block
- x and y coordinate of last significant level in scanning order
- Significance flags for 4×4 sub-blocks
- Significance map for 4×4 sub-blocks
- Absolute levels and signs



Adaptive coefficient scanning

- For 4×4 and 8×8 TB in intra CUs, scan depends on intra prediction mode (horizontal, vertical, diagonal)
- For all other blocks: Diagonal scan





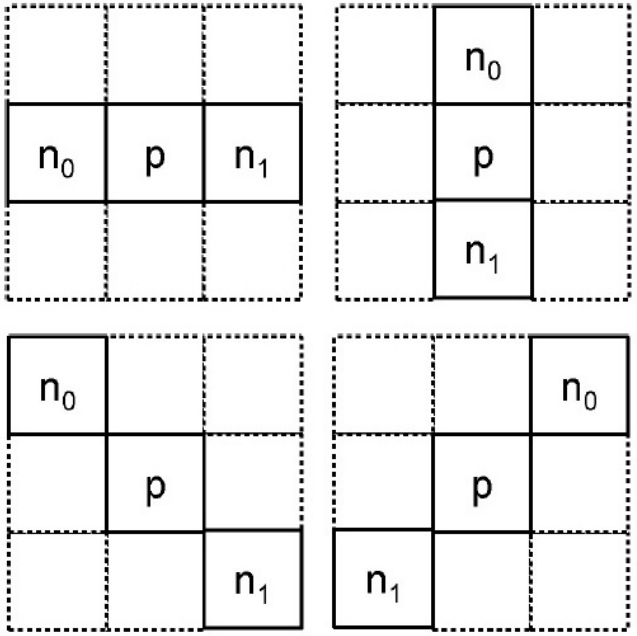
In-Loop Filtering

Deblocking filter

- Adaptive filter for reducing block edge boundaries
- Similar adaptation of boundary filter strength as in H.264 | MPEG-4 AVC
- Applied on 8×8 sample grid

Sample adaptive offset (SAO)

- Conditional adding of an offset to samples (offset are transmitted)
- Selected on region basis: Either not used or applied in one of two modes
- Mode 1: Band offset filtering
  - Offset depends on sample value
  - Split amplitude range into 32 bands
  - Offset values are transmitted for four consecutive bands
- Mode 2: Edge offset filtering
  - Choose one of 4 gradient directions
  - Classify sample into one of 5 categories based on neighbouring samples
  - Offset values are transmitted for 4 of these sample classes



Coding Efficiency Comparison with Prior Standards

Comparison of coding efficiency for intra-picture coding

- Selection of all features that contribute to coding efficiency
  - H.262 | MPEG-2 Video conforming to Main profile
  - H.263+ with advanced intra coding, deblocking filter, modified quantization
  - MPEG-4 Visual with MPEG-style quantization
  - H.264 | MPEG-4 AVC High profile with CABAC
  - **H.265 | MPEG-H HEVC Main profile**

- Apply same level of encoder optimization for fair comparison
  - Best possible coding efficiency for given syntax
  - Ignore constraints such as real-time operation

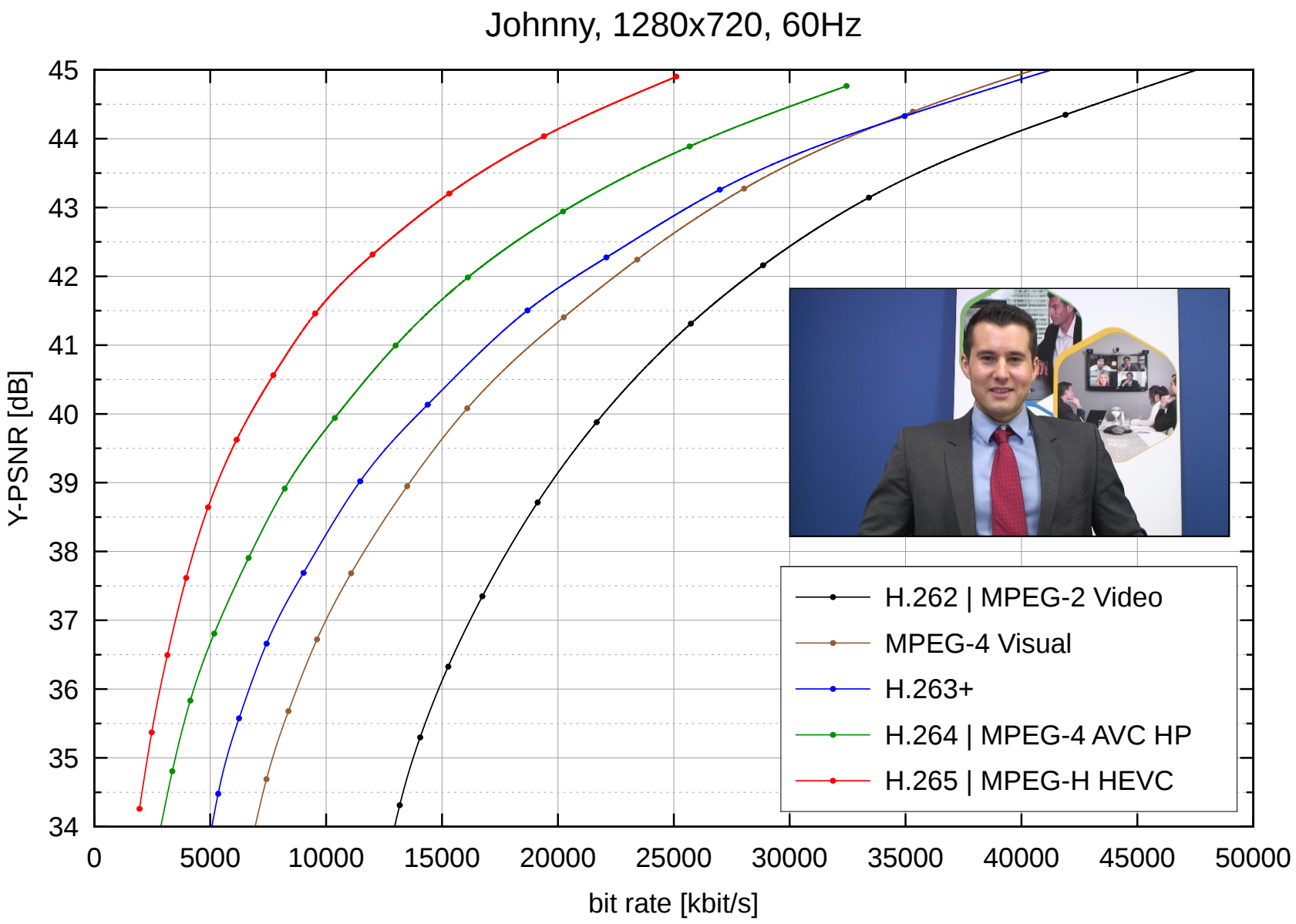
  $\Longrightarrow$ Use rate-distortion optimized quantization for all standards

  $\Longrightarrow$ Apply rate-distortion optimized mode decision where applicable

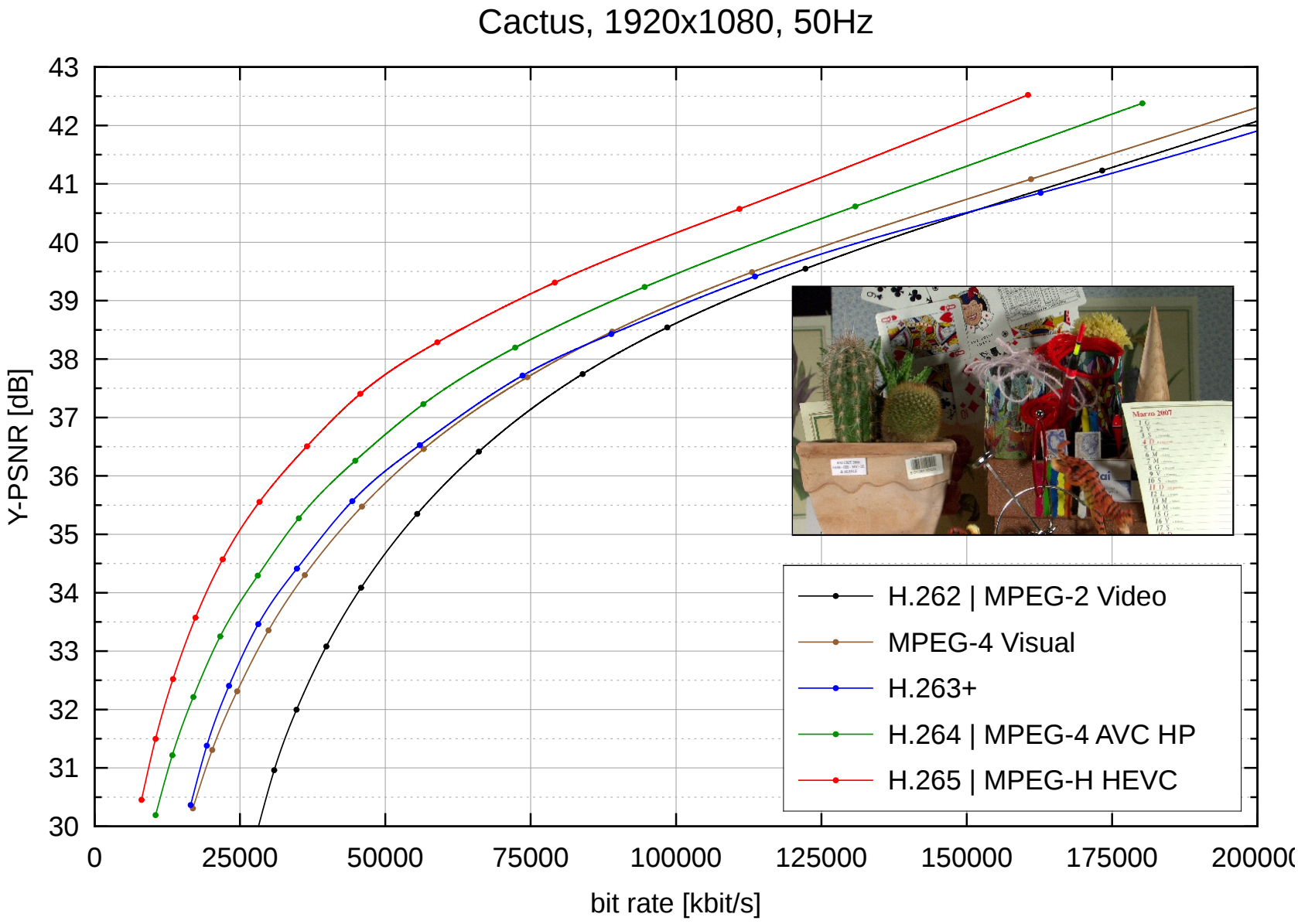
- General coding conditions
  - Encode 10 pictures of 12 video sequences (6 in 720p, 6 in 1080p)
  - Flat quantization matrices (quality is measured using PSNR)
  - Same quantization parameter for all macroblocks
  - Select Lagrangian parameter according to

$$\lambda = \text{const} \cdot \Delta^2 \qquad \text{(with experimentally determined factor)} \qquad (611)$$

Intra Coding Comparison – Sequence "Johnny"



Intra Coding Comparison – Sequence "Cactus"



Intra Coding Comparison – Summary

Bit-rate savings of H.265 | MPEG-H HEVC versus older video coding standards

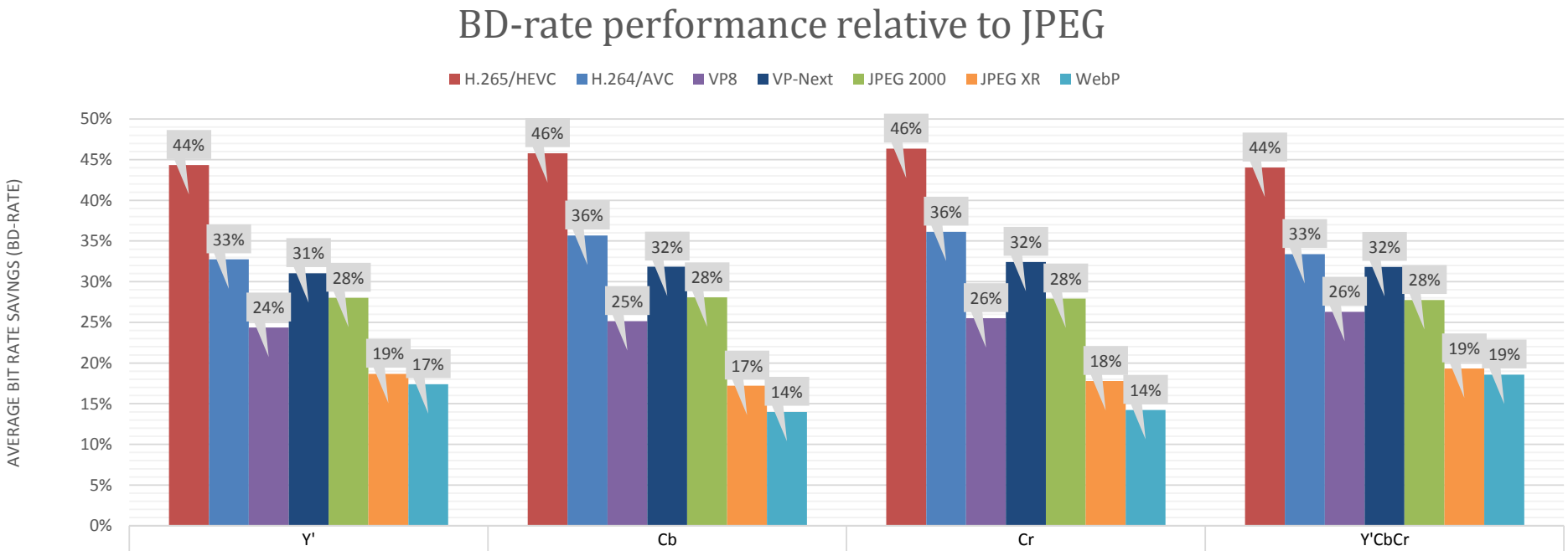
- Bit-rate saving at a PSNR value is obtained by interpolating the r-d curves
- Average bit-rate savings are obtained by averaging the savings for 100 PSNR values
- Highest savings are obtained for low bit rates
- Average bit-rate saving for all sequences are summarized below

codec	average bit rate savings relative to ...			
	H.264 / AVC	H.263+	MPEG-4	MPEG-2
H.265 / HEVC	25.1 %	40.3 %	45.2 %	57.9 %
H.264 / AVC		20.7 %	27.7 %	45.0 %
H.263+			9.5 %	31.9 %
MPEG-4				25.9 %

Intra Coding Efficiency versus JPEG Baseline

Coding efficiency comparison using available reference software versions

- Bit-rate savings relative to JPEG Baseline for JPEG test images



	Y'	Cb	Cr	Y'CbCr
H.265/HEVC	44%	46%	46%	44%
H.264/AVC	33%	36%	36%	33%
VP8	24%	25%	26%	26%
VP-Next	31%	32%	32%	32%
JPEG 2000	28%	28%	28%	28%
JPEG XR	19%	17%	18%	19%
WebP	17%	14%	14%	19%

[Nguyen, et. al., 2012]

Subjective Quality: Original (1024×704 samples, 4:2:0)

Subjective Quality (1:50 Compression): H.262 | MPEG-2 Video

Subjective Quality (1:50 Compression): H.263+

Subjective Quality (1:50 Compression): H.264/AVC

Subjective Quality (1:50 Compression): H.265/HEVC

Summary of Intra-Picture Coding in H.265 | MPEG-H HEVC

Intra-picture coding in H.265 | MPEG-H HEVC

- Partitioning of a picture
  - Partitioning into fixed-size coding tree blocks (typically 64×64 luma samples)
  - Quadtree-based partitioning into coding blocks and transform blocks
- Spatial intra prediction
  - 35 spatial intra prediction modes (35 directional modes)
  - Intra prediction is applied on transform blocks basis
- Transform and quantization
  - Integer approximation of DCT (special case: DST)
  - Supported transform sizes: 4×4, 8×8, 16×16, 32×32
  - Scalar quantizer with uniformly distributed reconstruction levels
- Entropy coding of transform coefficient levels
  - Coded block flags
  - Significance map: Last significant coefficient,
    significance flag for 4×4 sub-blocks, significance flags for levels
  - Absolute levels and signs
- In-loop filter: Deblocking and SAO filter