Hints on video coding

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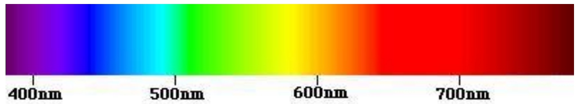
Summary

- Visual perception
- Analog and digital TV
- Image coding: hints on JPEG Standard
- Video coding
  - Motion compensation
  - MPEG: hierarchical data organization
  - MPEG-1
  - MPEG-2: scalability, profiles and levels
  - MPEG-4: content-based coding, sprite coding
  - Synchronization: MPEG-2 systems

Visual perception

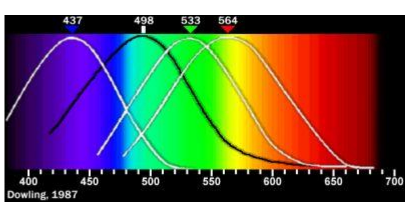
- Human eye is able to capture all wavelengths in the range 250-780 nm



- Eye sensitivity depends on the wavelength: for a given energy level, the radiation is perceptually received as more or less intense depending on λ
- The colour is a function of the wavelength and of the energy that it emits or reflects
- Two receptors: retinal cones and rods. Cones are more sensitive to wavelength, rods to energy

Colours

- Three families of cones exist, more sensible to short (blue), medium (green) and long (red) wavelengths



Normalized sensitivity of cones (white curves) and rods (black curve) as a function of wavelength

Colours

- All colours that the human eye is able to perceive can be creted by mixing three «primary» colours
- Several triples of colours can be used as primary
- Normally red, green and blue are used for the reason outlined above
  – RGB coding (Red, Green, Blue)

Definitions

- *Intensity*: radiated energy per unit area
- *Luminance*: photometric measure. It represent the radiated energy per unit area weighted by a sensitivity function related to human visual perception.
- *Brightness*: absolute value. It is a subjective attribute of visual perception in which a source appears to be radiating or reflecting light.
- *Lightness*: relative perceptive response. Brightness of an area relative to the brightness of a similarly illuminated area that appears to be white (highly transmitting)

Lightness e Brightness

- Intensity and luminance are objective quantities, that can be measured with proper instruments
- Brightness and lightness are subjective quantities: they depend on many factor (among the others the luminance of the environment in which the human eye is) and are different from person to person
- Luminance perception is non linear
  - The lightness of a source whose luminance is 18% of the one of the reference source is roughly 50%

Luminance and crominance

- R, G and B components of a colour are strongly correlated:
  - This redundancy can be exploited to reduce the amount of information neeeded to represent a given colour
- Analog TV standard use separate signals for:
  - Luminance
    - Image representation using a grey scale system
  - Crominance
    - Colour information

Luminance and crominance

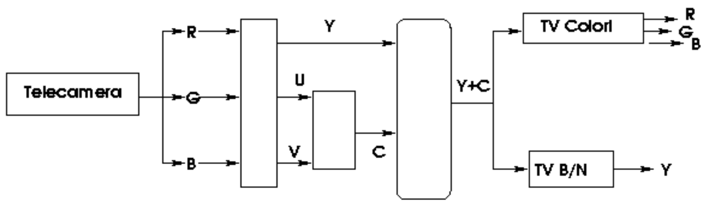
- Luminance and crominance are almost non correlated
- Luminance contains info on lightness and brightness,
  - For example defines figure contours
- Since the human eye is particularly sensible to lightness and brightness, the most fundamental image information is concentrated on the luminance

Analog TV

- PAL (Phase Alternate Line) standard is based on YUV coding
  - Y is the luminance, U and V are the two crominance
- YUV components can be obtained from RGB components via a linear transformation
  - $Y = 0.3R + 0.59G + 0.11B$
  - $U = 0.493 (B – Y)$
  - $V = 0.877 (R – Y)$
- NTSC (National Television System Commitee) standard exploits YJQ
- RGB to YJQ transformation is also linear but wih different coefficients for J and Q
  - $Y = 0.3R + 0.59G + 0.11B$
  - $J = 0.74 (R – Y) – 0.27 (B – Y)$
  - $Q = 0.48 (R – Y) + 0.41 (B – Y)$

Analog TV

- Black and white analog TV exploits only the luminance signal, colour TV also the crominance



TV standards

PAL		NTSC
4:3	Aspect Ratio	4:3
625	Number of lines per frame	525
25	Number of frames/s	29.97
8 MHz	Transmission bandwidth	6 MHz

Digital video

- The ITU-R 601 standard defines a digital format for PAL and NTSC
- Both formats have 720 samples per line
  - Corresponding sampling frequency is 13.5 MHz
- Y, U and V components are independently sampled
  - Since U and V are less important, the are sub-sampled with respect to Y with ratios 4:2:2 or 4:1:1
- Using 8 bit to represent each component of each sample, the overall bitrate is
  - (13.5 + 2*6.75)106sample/s*8bit/sample = 216 Mbit/s
- More precisely, in NTSC the useful lines (no retracing) are 486 with 720 samples per line
  - 720sample/line*486lines*30frame/s*8bit/sample = 84Mbit/s (luminance only)

Digital video

- HDTV standards exploit up to
  - 1440 or 1920 samples per line
  - 1152 lines per frame
  - 60 frames/s
- Resulting bitrate can easily exceed 1 Gbit/s
  - Only professional studios can store, transmit and elaborate flows at this speed
  - Compression techniques become fundamental
- Videoconferencing standards
  - CIF (H.261): 4:1:1 ratios.
    - 352 sample/line, 288lines/frame (luminance). 36Mbit/s
  - QCIF
    - 176 sample/line or 144lines/frame (luminance). 18Mbit/s

Video compression

- Video presents a high level of redundancy
- Statistical redundancy :
  - *Spatial*: adjacent pixels in the same frame are correlated (intra-frame compression)
  - *Temporal*: pixel in the same positon in consecutive frames are correlated (inter-frame)
- Perceptive redundancy: related to characteristics and features of human vision system
- Redundancy can be exploited to compress video

Compression

- Entropic coding
  - Do not exploit info on the source characteristics
    - Huffman algorithm
      - Shorter representation for more likely symbols
    - Run-Length encoding (RLE)
      - exploits correletion among adjacent elements
      - Long sequences of symbols with the same value are coded as pairs (value, number of repetitions)
  - Lossless
  - Level of compression somehow limited

Compression

- Source coding
  - Predictive
    - exploits correlation among adjacent elements,
    - e.g., the dynamics of the difference is smaller than the dynamics of the original signal (like DPCM)
  - Transform
    - examine the image in a domain in which the redundancy contained in the information can be better highlighted
    - FFT (Fast Fourier Transform) and DCT (Discrete Cosine Transform) highlight the fact that most of the image information is concentrated in low frequency spectrum components

Compression

  - Vectorial: takes a block of data (vector) and maps it to the element that best match it in a pre-defined codebook
    - Block can be mono or bi dimensional
  - Layered: the image is hierarchically decomposed in several layers
    - Each layer enhances the image quality of the previously defined layers
    - The decomposition is obtained through sampling at different frequencies or in different sub-bands
- Source coding is often lossy
- Very often hybrid coding techniques are used:
  - Several compression schema are used in series to obtain better performance

JPEG standard

- Image compression standard approved in 1992 by the “Joint Photographic Experts Group” of ISO
- Lossy coding exploiting the human vision perception to reduce the redundancy
- The compression ratio can be varied depending on the target quality level of the compressed image

JPEG

- The algorithm operates independently on luminance and crominance (represented with three different matrices)
  - It may be necessary to exploit the transformation RGB->YUV or RGB->YJQ
- The three matrices are divided in 8x8 blocks
- The DCT transform is applied to each block
  - Linear transformation (lossless)
  - Modifies the representation system of the image
  - Image represented in the frequency domain
- A quantization block is applied to the transform
  - Lossy

JPEG

- The “continuous” component of the block is stored in the upper left corner of the matrix
- Moving from left to right and from top to botton the elements of the transformed block represent increasing frequencies
- Low frequency components contain the most significant information on the image
  – They are quantized with a better granularity
- The DC “component” is coded as a difference with respect to the DC component of the previous block

JPEG

- Most of the high frequencies components are negligible or null due to the coarser quantization
- AC coefficient are encoded according to RLE, following a zig-zag order in the matrix, to put in sequence the high frequencies null coefficients
- Finally, the pairs (value, number of repetitions) are coded according to the Huffman method
- The quantization granularity determines the compression ratio and the level of degradation of the compressed image
- Coding and decoding have the same complexity

Example

Matrice DCT

150	88	45	12	6	3	1	0
94	73	38	10	4	1	0	0
50	47	26	8	7	3	0	0
17	8	8	3	2	1	0	0
12	5	4	0	0	0	0	0
1	2	1	1	0	0	0	0
1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0

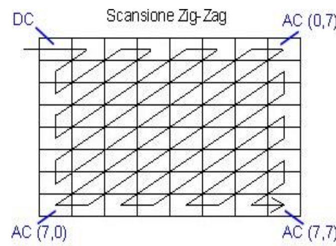
Matrice di Quantizzazione

1	1	2	4	8	16	32	64
1	1	2	4	8	16	32	64
2	2	2	4	8	16	32	64
4	4	4	4	8	16	32	64
8	8	8	8	8	16	32	64
16	16	16	16	16	16	32	64
32	32	32	32	32	32	32	64
64	64	64	64	64	64	64	64

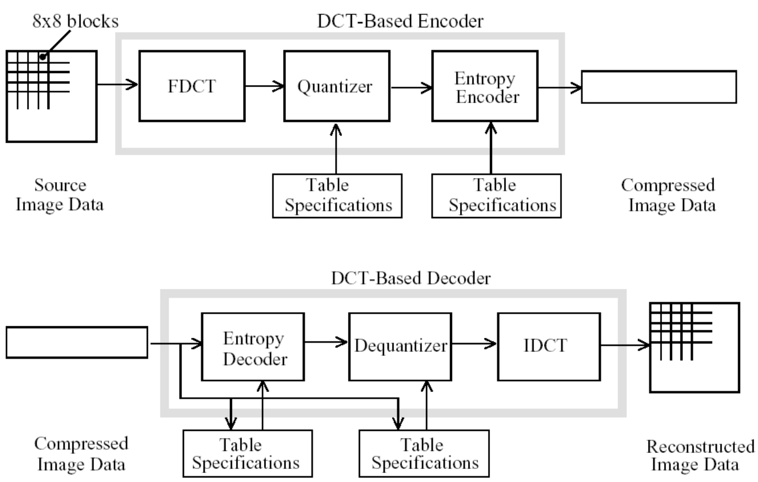
Matrice quantizzata

150	88	23	3	1	0	0	0
94	73	19	3	1	0	0	0
25	24	13	2	1	0	0	0
4	2	2	1	0	0	0	0
2	1	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

Scansione Zig-Zag



Coder and decoder



Da [1]

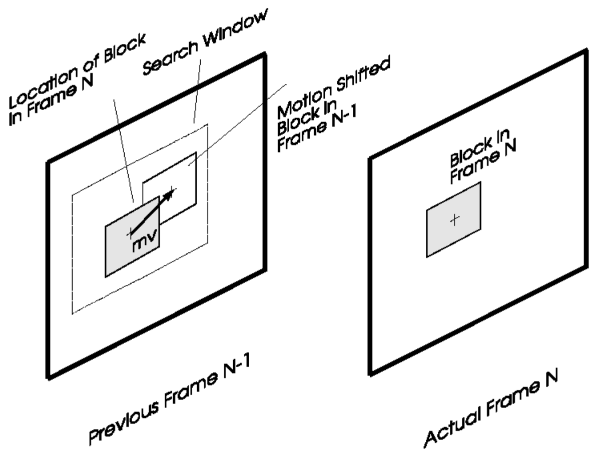
MPEG coding

- A video stream is composed by a sequence of images (frame)
- Single frames are compressed according to a scheme similar to JPEG
- Temporal correlation among frames is exploited using techniques such as
  - differential coding and prediction
  - motion compensation (to identify object movement)

Motion compensation

- Frame N is divided in blocks
- For each block, a motion vector is estimated
  - All blocks in frame (N-1) with adjacent positions to the considered block in frame N are examined to select the most similar one
- The block is coded as the difference with respect to the previous block plus the motion vector
- Works well for translation, not well for zoom, rotation
- Block is not a physical object
- Coding operation is more complex and time consuming than decoding

Motion compensation)

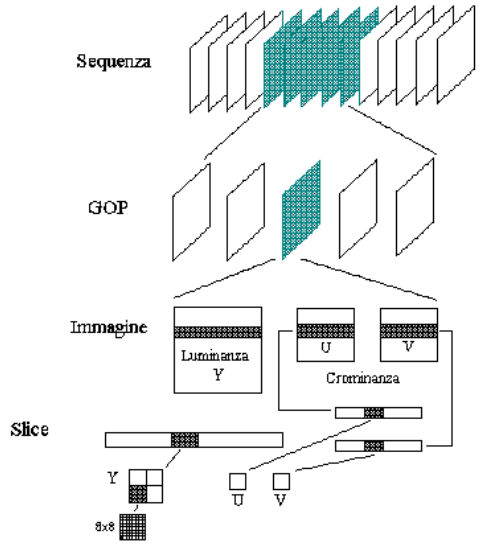


From ref [2]

MPEG – Data organization

- Data are hierarchically organized in layers
- Each layer supports a signal processing function and a logic function
- Six layers
  - Sequence
  - Group of Pictures (GOP)
  - Picture
  - Slice
  - Macroblock
  - Block

MPEG – data organization



Sequence and GOP

- The sequence defines the video flow in terms of
  - Frame size, number of frames per second and bitrate
- Within each sequence, GOPs are identified
  - Groups of contiguous, independent, pictures classified as I, P, B:
    - Intra-pictures
    - inter-frame Predicted pictures
    - Bi-directional inter-frame predicted pictures
  - A GOP can contain a variable number of I, I and P, or I, P and B pictures

Pictures

- I pictures
  - Coded/decoded in isolation, with no reference to other images
  - Can be used as a reference to code P or B pictures
  - Identify the starting point of a GOP
  - Useful to support random access
  - Limit error propagation
  - Compression level limited
- P pictures
  - Coded referring to the nearest I or P picture
  - Can be used as a reference to code P or B pictures
- B pictures
  - Coded referring to two (previous or next) I or P pictures
  - Never used as a reference
- A large number of P and B pictures
  - permit to increase the compression ratio but also coding delay and complexity
  - makes it more difficult the random access
  - makes the flow more sensitive to errors

Pictures

- Since B images refer also to pictures to be played back later, the visualization order is different from the coding and transmission order
- Example
  - Visualization order: I0 B1 B2 P3 B4 B5 P6
  - Dependencies:
    - I0 -> none
    - P3 -> I0
    - B1 and B2 -> I0 e P3
    - P6 -> P3
    - B4 e B5 -> P3 e P6
  - Coding and transmission order: I0 P3 B1 B2 P6 B4 B5

Slices

- Slices are portion of images that include an integer (variable) number of macroblocks
- A slice does not contain spatial references to other slices
  - Can be decoded independently (in isolation)
- Exploited for synchronization purposes

Macroblocks

- The Macroblock (MB) is the fundamental unit for motion prediction
- In MPEG-1 the macroblock size is 16x16 pixels
- Each macroblock can be of type:
  - *Skipped*: it is identical to the MB in the same position in the reference image
    - It is neither coded nor transmitted
  - *Inter*: differentially coded with respect to another MB in the reference image
    - motion vector, values of the difference and quantization levels are transmitted
  - *Intra*: coded in isolation
    - Samples values and quantization levels are transmitted

Macroblocks

- The MB type is a function of the picture type:
  - Type I: only Intra MB are used
  - Types P and B: can exploit Intra, Inter and Skipped MB
- For B pictures and Inter MB, the prediction can be:
  - *Backward:* the motion vector refer to a MB of a past picture
  - *Forward:* the motion vector refers to a MB of a successive picture
  - *Interpolated:* exploit two motion vectors, one referring to the a past picture one to a following picture; the prediction is computed on the average values of the two MBs

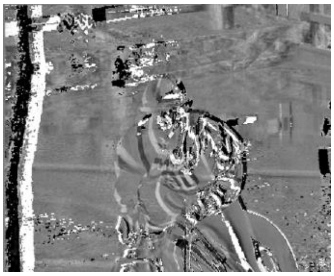
Macroblocks

- The standard does not specify how to compute the motion vectors and the criteria to choose the MB type
- Usually, block matching techniques are used:
  - The algorithm looks for the motion vector that minimizes the energy of the difference between the block to be coded and the one to which the vector refer to
  - If the energy difference is below a pre-defined threshold the Inter MB is chosen (differences are transmitted)
  - Otherwise, an Intra MB is chosen (the whole MB is transmitted coded in isolation)
- Compression more difficut than decompression

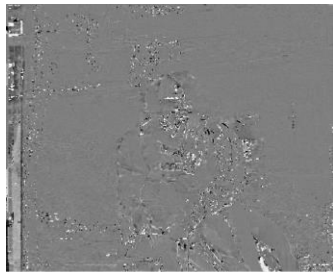
(a) Frame N to be coded

(b) Frame N-1 (with motion vector)

From ref [2]



(c) «Difference» picture without motion compensation (all motion vectors are null)



(c) «Difference» picture with motion compensation

Blocks

- *Blocks* are the fundamental data unit over which the spatial redundancy is applied
- Block size is 8x8 pixels
- Blocks are represented as one luminance matrix and two crominance matrices
- Crominances are sub-sampled in ratios 4:1:1. Thus a mB contains 4 luminance and 2 crominance 8x8 matrices
- The single block coding follow the JPEG standard: DCT transform, quantization,differrential coding for the DC component, RLE and entropic compression with zig-zag scanning for AC components

MPEG-1 standard (1992)

- Defined for VHS quality for bitrate up to 1.5Mbit/s (close to an audio CD bitrate)
- Interlaced pictures are not supported
- The MPEG-1 "constrained parameter set" (set of reference for standard implementation) is:
  - Pixel per line ≤ 768
  - Lines per picture ≤ 576
  - Macroblocks per picture ≤ 396
  - Macroblocks/s ≤ 9900
  - Pictures/s ≤ 30
  - Bitrate ≤ 1.856 Mbit/s

MPEG-2 standard (1994)

- Defined for digital TV and HDTV, CD storing, terrestrial and satellite broadcasting, interactive retrieval
- Main features:
  - Video quality not worse than PAL/NTSC
  - Support for interlaced pictures
  - Video scalability (the picture quality can be progressively reduced in case of transmission error/losses)
  - Compatible with MPEG-1
  - Definition of Profiles and Levels to ease the interoperability among partial implementation of the standard

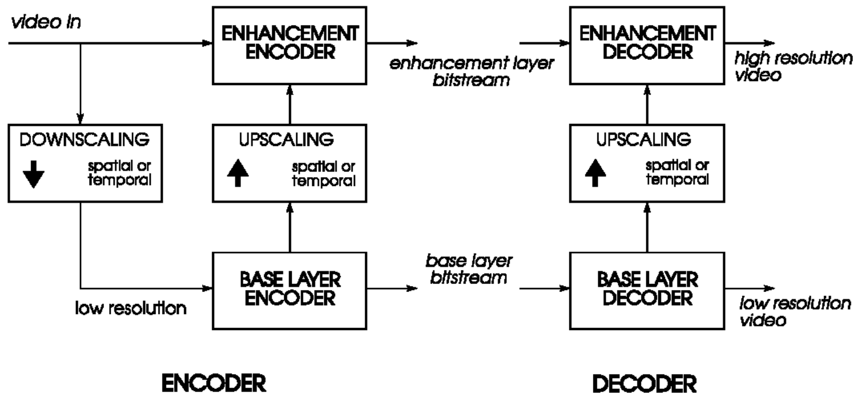
Video scalability

- Data flow is decomposed in a “base” layer and in “enhancement” layers
- Successive layers enhance the offered video quality with respect to the previous layers
- A receiver may decode only a given number of layers, depending on the amount of available resources (display, processor, etc.)
- Video scalability may be SNR, spatial or temporal, depending on the decomposition criteria adopted
- Base layer may get better service (e.g. high priority) in the transmission system

Video scalability

- SNR: base layer uses a coarse granularity for DCT coefficients,enhanced layers use a more fine granularity
- Spatial: changes the picture spatial resolution
  - for example, the base layer subsamples the picture, enhanced layers transport additional pixel information
  - useful to support display of different size
- Temporal: changes the temporal video resolution
  - for example enhanced layers increas the number of images/s
  - useful also for stereoscopic vision (a left and a right channel for the same picture)

Scalable coder and decoder



From ref [2]

Profiles and levels

- A profile defines a set of supported algorithms (additional to those of lower profiles)
- A level defines the supported parameter range (picture size, number of pictures/s, bitrate)
- The pair profile-level identifies the decoder supported functionalities
- All decoders should support at least the MAIN profile with level MAIN

Profiles

HIGH	All the features of the SPATIAL profile plus support for: • Coding with 3 levels of spatianl and SNR scalability • Colour coding YUV 4:2:2
SPATIAL scalable	All the features of the SNR profile plus support for: • Scalable spatial coding (2 levels) • Colour coding YUV 4:0:0
SNR scalable	All the features of the MAIN profile plus support for: • Scalable SNR coding (2 levels) • Colour coding YUV 4:2:0
MAIN	Non scalable coding algorithms plus support for: • Interlaced video • Random access • Bi-directional prediction (B-pictures) • Colour coding YUV 4:2:0
SIMPLE	As the MAIN profile but: • Does not support bi-directional prediction • Colour coding YUV 4:2:0

Levels

	HIGH	**HIGH 1440**	**MAIN**	**LOW**
Samples/line	1920	1440	720	352
Lines/frame	1152	1152	576	288
Frames/s	60	60	30	30
Bitrate (Mbit/s)	80	60	15	4

MPEG-4 standard (1998)

- Objectives
  - Robustness in error prone environment (wireless networks/links, congested links, etc.)
  - High interactivity level, with the possibility of modify and store data in a very flexible way
  - Efficient coding of both natural and syntetich infos
  - Efficient compression, with support for bitrate as low as 64kbit/s
- “Content Based” approach
  - Separately identifies and codes objects in a video stream
  - Video is composed by “putting together” the various objects

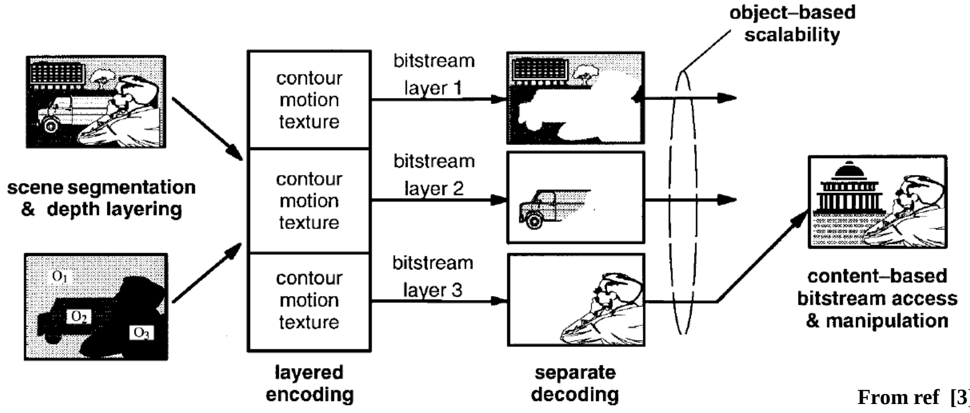
Video objects

- A video object is a sequence of bitmap of any shape
  - “Video Object Planes”
- Shape and position of VOP vary over time
- For every object the transmitted infos are:
  - Shape
  - Trasparency
  - Spatial coordination
  - Scaling and rotation

Video objects

- Every object is coded on a separate stream
- The receiver can:
  - Decode only some objects in the flow
  - Add new objects
  - Modify the representation parameters of objects
- It is also possible to refer to objects contained in a local library at the receiver

Video objects



From ref [3]

Other objects

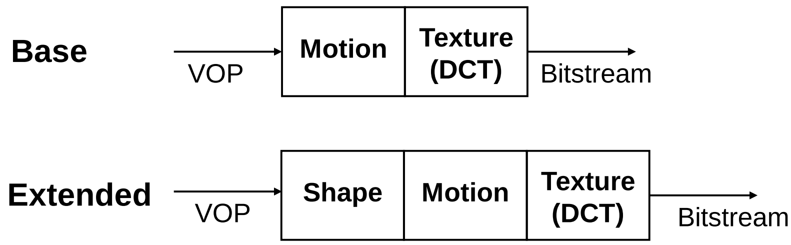
- Audio objects
  - Sounds produced by the different instruments in an orchestra
  - Voices in a conversation
- Synthetic objects
  - Superimposed text
  - Computer animated objects
    - Faces, human figures, "texture mapped wire-grid"

Structure

- The standard supports rectangular pictures as MPEG-1 e MPEG-2
- "VLBV Core" is a portion of the standard that defines the real time coding technique of flows:
  - non content-based
  - at very low bitrate (5 – 64 kbit/s)
  - with high error resilience
  - at low delay
  - at low complexity
- "HBV Core" provides the same functionalities but with higher bitrate (few Mbit/s)

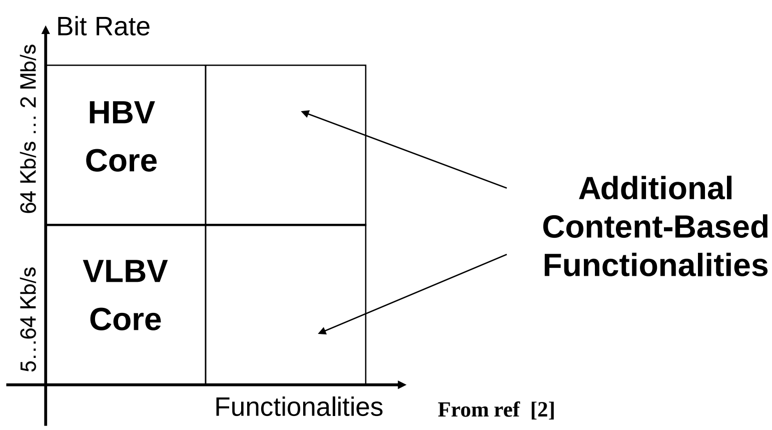
Structure

- Other portions of the standard add content-based funtionalitis to VLBV e HBV coder and decoder
- In the below example, a VLBV base coder adds content-based infos thanks to a block that defines the VOP shapes



From ref [2]

Structure



From ref [2]

VLBV = Very Low Bitrate Video

HBV = High Bitrate Video

Sprite Coding

- *Sprite Coding* is a technique that exploits the presence of static, large size portions of the picture
  - Background or landscape
- The sequence is decomposed in “foreground” and “background” sprite
- For the foreground, all object parameters are transmitted every frame
- For the background, the full bitmap is transmitted only once
  - In the other frames only the motion of the camera framing the background is transmitted

Sprite Coding

- In the following example,
  - the foreground sprite is the tennis player
  - the background is the field and the audience
- Transmission
  - First, frame 200 containing all background info
  - Later, all the parameters of the foreground and the motion parameter of the background (translation, rotation, zoom…)

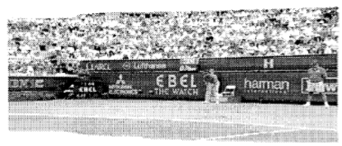
Frame 1

(a)

Frame 50

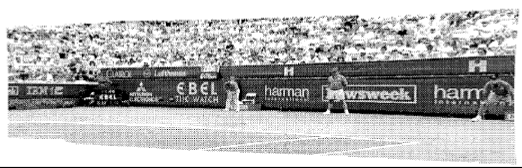
(b)

Frame 100



(c)

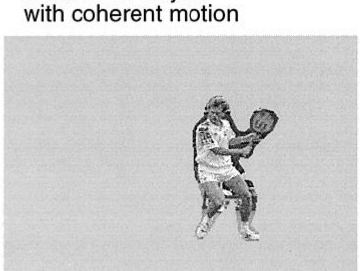
Frame 200



From ref [3]

Foreground and background

foreground
flexible 2D–object
with coherent motion



SA–DCT: 12 000 bit/frame
motion: 200 bit/frame
contour: 500 bit/frame

=> ca. 320 kbit/s

background
rigid 3D–background
with global camera motion

SA–DCT: 7000 bit/frame
motion: 140 bit/frame

=> ca.180 kbit/s

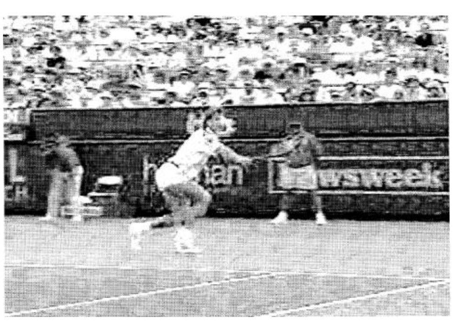
From ref [3]

Performance

- Sprite coding technology permits to obtain very high compression ratios with a good quality
- The need to separate foreground and background makes the technique easier to be used in multimedia database, where off-line processing is easy
  - Not perfectly suited for real time broadcasting

Performance

- Same picture extracted from a sequence coded according to MPEG-1 (left) and MPEG-4 (right) for the same bitrate (1 Mb/s)



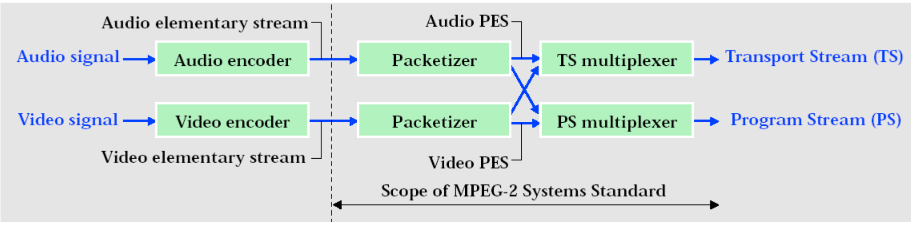
From [3]

Synchronization: MPEG-2 Systems

- It is the part of the standard that defines the syntax and the sematics of the bitstream
- Specify how to multiplex several flows on the same bitstream and how to synchronize them during the decoding phase
- The multiplexing criteria (how to multiplex packets generated by different sources) is not specificied
- *An Elementary Stream* is the coded flow produced by a single video or audio source

MPEG-2 Systems

- Once segmented in packets, it is named *Packetized Elementary Stream* (PES)
- PES are multiplexed into a *stream*
- Two types of stream: Program Stream and Transport Stream



Da "Broadcast Technology" no.11, Summer 2002

Time-stamp

- PES include synchronization time-stamp in the header:
  - SCR (System Clock Reference): provides the time reference for the demultiplexing of PES of a program
  - DTS (Decoding Time Stamp): specify the time instant at which each pictures should be decoded
  - PTS (Presentation Time Stamp): specify the time instant at which each picture should be visualized

Stream

- Program Stream (MPEG-1 e MPEG-2):
  - Multiplex audio and video source with a common base time, equivalent to a TV program
  - Defined to store info on CDs and DVDs
  - Based on PS Packs packets *PS Packs* of variable size, ranging from 1 to 64 Kbyte
- Transport Stream (solo MPEG-2):
  - Multiplex a given number of programs, each one with its time base
  - Defined for broadcasting TV via cable, satellite, etc.
  - Fixed packet size of 188 byte

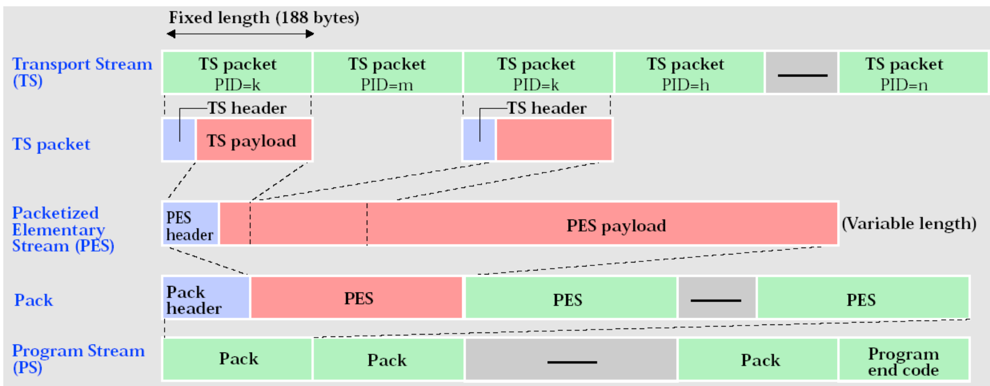
Transport Stream

- Every packet in the stream contains a “Packet ID” (PID) that identifies the elementary stream to which it belongs to
- PID 0 is reserved and transports the info related to the “Program Association Table” (PAT)
- The PAT associates every program contained in the stream to a “Program Map Table” (PMT), specifying the transported PID
- The PMT lists all PID of the elementary stream of the program (audio, video, …)

Demultiplexing

- The decoder, to demultiplex program **P**:
  - Extract packets with PID 0 and rebuilds the PAT
  - In the PAT it reads the PID *X* of the packets containing the PMT of program **P**
  - Extracts packets with PID *X* and builds the PMT of program **P**
  - Extracts all packets with one of the PID listed in the PMT (*Y*, *Z*, etc.)

Data organization



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