Insight, Analysis, and Advice on Signal Processing Technology

Introduction to Video Compression (ESC-368)

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Outline

Motivation and scope

Still-image compression techniques

Motion estimation and compensation

Reducing artifacts

Color conversion

Comparing performance and efficiency

Conclusions

Motivation and Scope

Consumer video products increasingly rely on video compression
- DVDs, digital TV, personal video recorders, Internet video, multimedia jukeboxes, video-capable cell phones and PDAs, camcorders…

Video product developers need to understand the operation of video "codecs"
- To select codecs, processors, software modules
- To optimize software

This presentation covers:
- Operation of video codecs and post-processing
- Computational and memory demands of key codec and post-processing components

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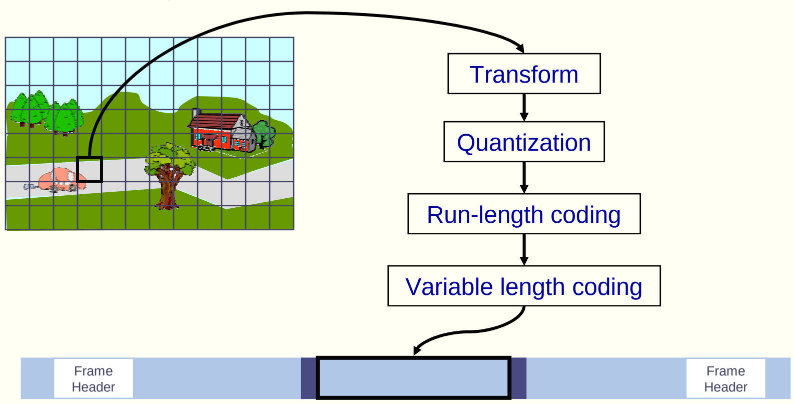
Still-Image Compression

Still-image compression
- Still-image techniques provide a basis for video compression
- Video can be compressed using still-image compression individually on each frame
- E.g., “Motion JPEG” or MJPEG

But modern video codecs go well beyond this
- Start with still-image compression techniques
- Add motion estimation/compensation
  - Takes advantage of similarities between frames in a video sequence

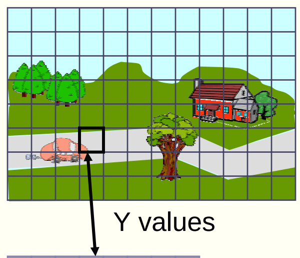
Still-Image Compression

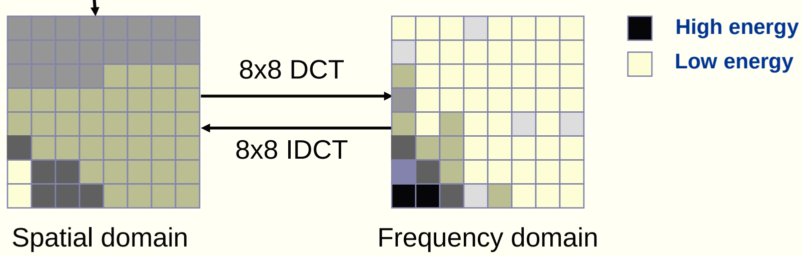


Typical Still-Image Compression Data Flow

Block Transform: 8x8 DCT

- 8x8 DCT blocks applied on Y, U, and V planes individually
- The energy is concentrated in the low frequencies
- Perceptual information also concentrated in low frequencies





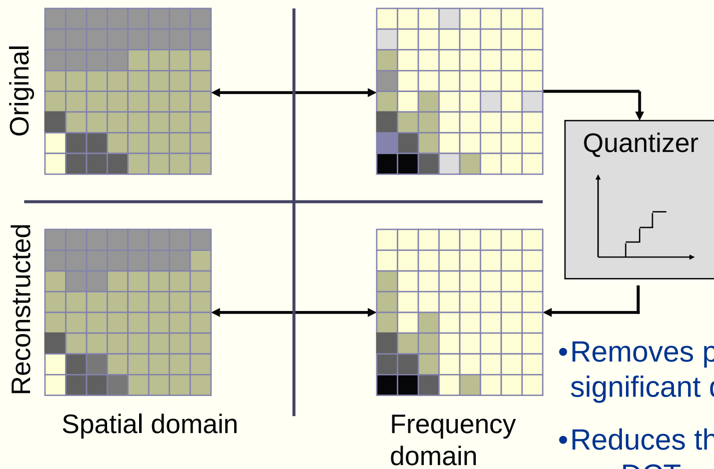
Block Transform: Resource Reqt's

Compute load:

- Up to 30% of total video decoder processor cycles
- MPEG-4 CIF (352x288) @ 30 fps:
  - 71,280 DCTs/s
  - ~40 MHz on a TMS320C55x DSP
  - ~10 MHz if using TMS320C55x DCT accelerator
- Many implementation and optimization options
  - Can make compute requirements hard to predict

Memory usage: negligible

Quantization



- Removes perceptually less significant data
- Reduces the number of bits per DCT coefficient

Quantization: Resource Reqt's

Quantization (encoder) and dequantization (decoder and encoder) have similar loads

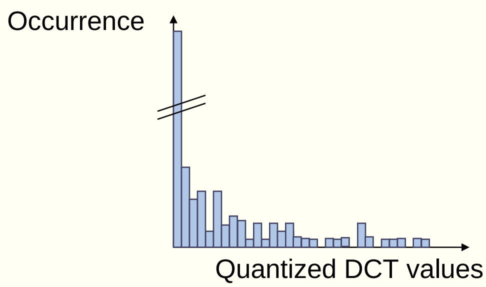
Compute load:

- From 3% to about 15% of total decoder processor cycles
  - Typically near the lower end of this range
- MPEG-4 CIF (352x288) @ 30 fps:
  - ~10 MHz on a TMS320C55x DSP (estimated)

Memory usage: negligible

Coding Quantized DCT Coefficients

Goal: Reduce the number of bits required to transmit the quantized coefficients



Observation: Unequal distribution of quantized DCT coefficient values

Variable Length Coding (VLC/VLD)

Allocates fewer bits to the most frequent symbols (e.g., using Huffman)

Integer number of bits per symbol

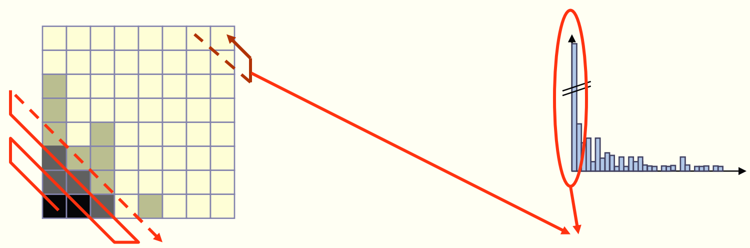
- Not the most efficient coding method
- Arithmetic coding more efficient, but expensive
- Run-length coding improves efficiency of VLC/VLD for image and video coding

Symbol	Frequency	Code
A	22	1
B	16	011
C	9	0101
D	7	0100
E	4	0011
F	2	0010
...	...	...

Run-Length Coding

Encodes value and number of successive occurrences

Takes advantage of the high number of recurring zeros



20,1 ; 18,1 ; 20,1 ; 18,4 ; ... ; 0, 37

VLC/VLD Processing Requirements

VL decoding much more computationally demanding than VL encoding

VLD compute load:

- Up to 25% of total video decoder processor cycles
- MPEG-4 CIF (352x288) @ 30 fps, 700 kbps:
  - ~15-25 MHz on a TMS320C55x DSP (estimated)
- About 11 operations per bit on average

Memory usage

- A few KB of memory for lookup tables
- More for speed optimizations

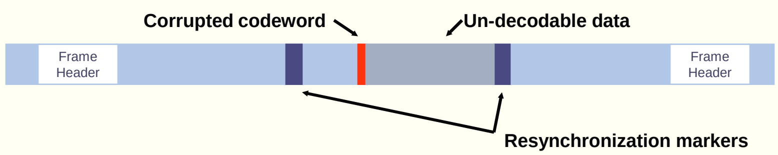
Resynchronization Markers

Without markers, a single bit error in the coded bitstream prevents decoding of the rest of the frame

- Size of a corrupted variable-length code word is unknown
- Therefore, the start of the next code word (and all following code words) is unknown

Resynchronization markers help the decoder recover from bitstream errors

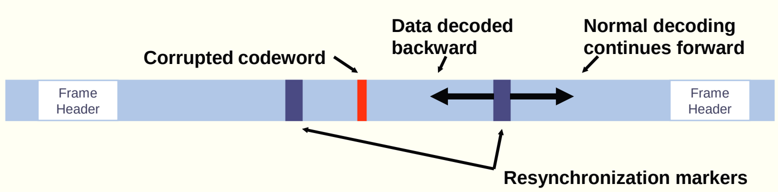
- Provide a known bit pattern interspersed throughout the bitstream
- In case of an error, decoder searches for next marker, then continues decoding



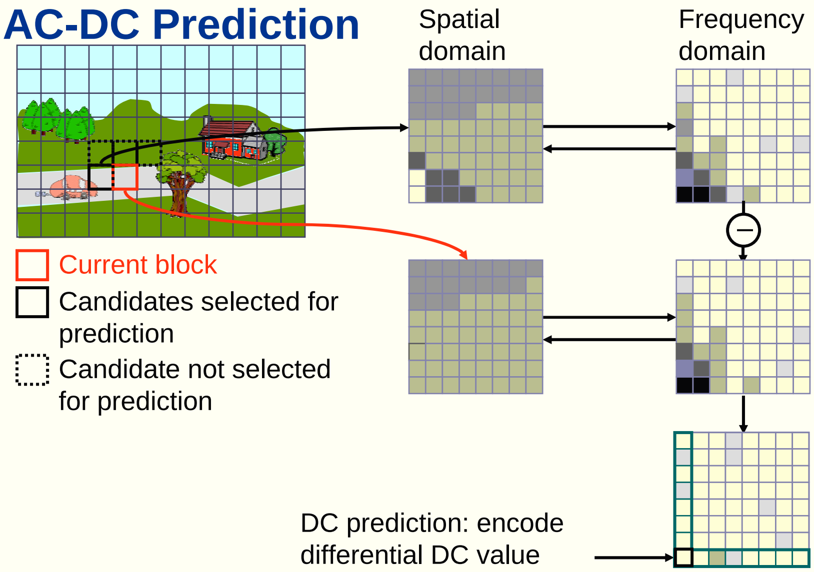
Reversible VLC

Reversible VLC, in conjunction with resynchronization markers, further assists error recovery

- Code words can be decoded forward and backward
- In case of error, data can be decoded backward from the next resynchronization marker
- More data is recovered compared to resynchronization markers alone



AC-DC Prediction



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AC-DC Prediction

AC-DC prediction cannot be used in conjunction with motion compensation

- **Used mostly for compressing a single image**
- DC prediction used in JPEG

AC-DC prediction often uses simple filters to predict each coefficient value from one or more adjacent blocks

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AC-DC Prediction: Processing Reqt's

Compute load:

- DC prediction has negligible load
- AC-DC prediction used in about 8% of frames in typical video
  - Negligible average load (~2% of processor cycles in decoder)
  - Substantial per-frame load (~20-30% of cycles required to decode a frame that uses AC-DC prediction)

Memory usage:

- Under 2 KB for CIF (352x288) resolution
  - But more memory (up to 10 KB) can result in faster code
- May be overlapped with other memory structures not in use during prediction

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Motion Estimation and Compensation

Still image compression ignores the correlation between frames of video

- JPEG achieves ~10:1 compression ratio
- Wavelet transform-based image coding reaches compression ratios up to ~30:1

Adding motion estimation and compensation results in much higher compression ratios

- Good video quality at compression ratios as high as ~200:1

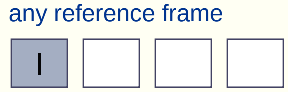
Motion Estimation and Compensation

Requires at least one "reference frame"

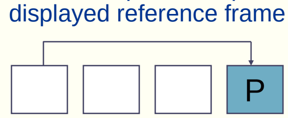
- Reference frame must be encoded before the current frame
- But, reference frame can be a future frame in the display sequence

Three kinds of frames: I, P, and B

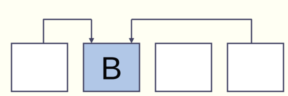
- I frame is encoded as a still image and doesn't depend on any reference frame



- P frame depends on previously displayed reference frame



- B frame depends on previous and future reference frames



Typical Sequence of I, P, B frames

Display order (left to right)

Encoding order (top to bottom)

I													
				P									
	B												
		B											
			B										
								P					
					B								
						B							
							B						
												P	
									B				
										B			
											B		
													I

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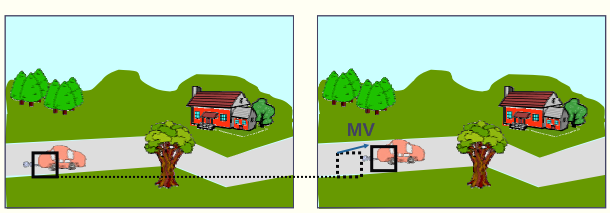
Motion Estimation

Predict the contents of each macroblock based on motion relative to reference frame

- Search reference frame for a 16x16 region that matches the macroblock
- Encode motion vectors
- Encode difference between predicted and actual macroblock pixels



MV= Motion Vector

Reference frame **Current frame**

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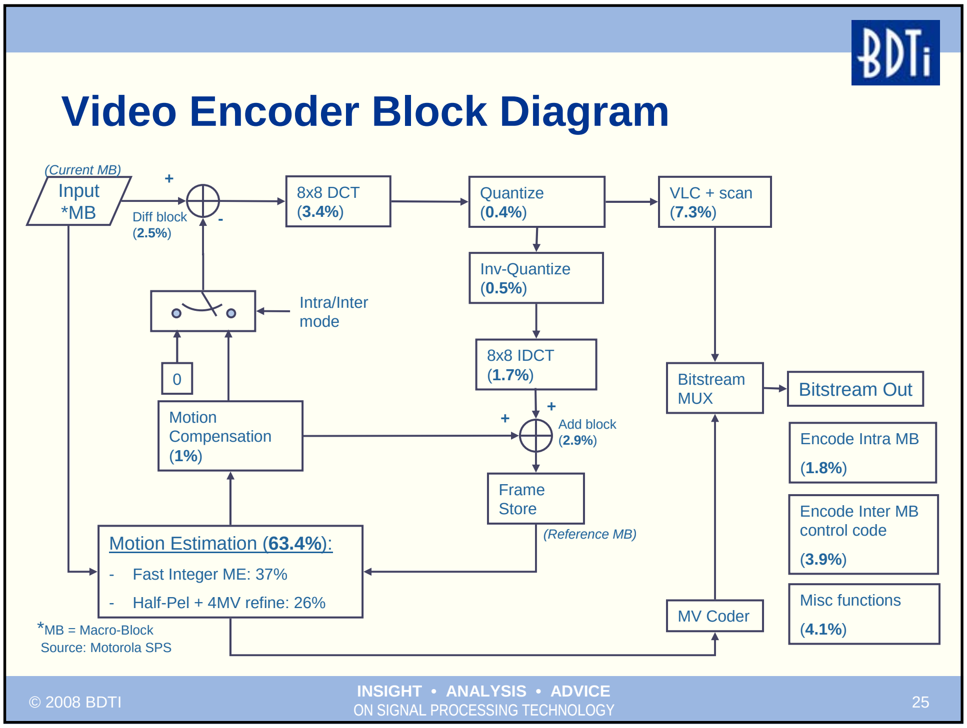
Video Encoder Block Diagram
(Current MB)
Input *MB
+
-
Diff block (2.5%)
8x8 DCT (3.4%)
Quantize (0.4%)
VLC + scan (7.3%)
Inv-Quantize (0.5%)
Intra/Inter mode
0
8x8 IDCT (1.7%)
Bitstream MUX
Bitstream Out
Motion Compensation (1%)
+
+
Add block (2.9%)
Encode Intra MB (1.8%)
Frame Store
(Reference MB)
Encode Inter MB control code (3.9%)
Motion Estimation (63.4%):
- Fast Integer ME: 37%
- Half-Pel + 4MV refine: 26%
MV Coder
Misc functions (4.1%)
*MB = Macro-Block
Source: Motorola SPS
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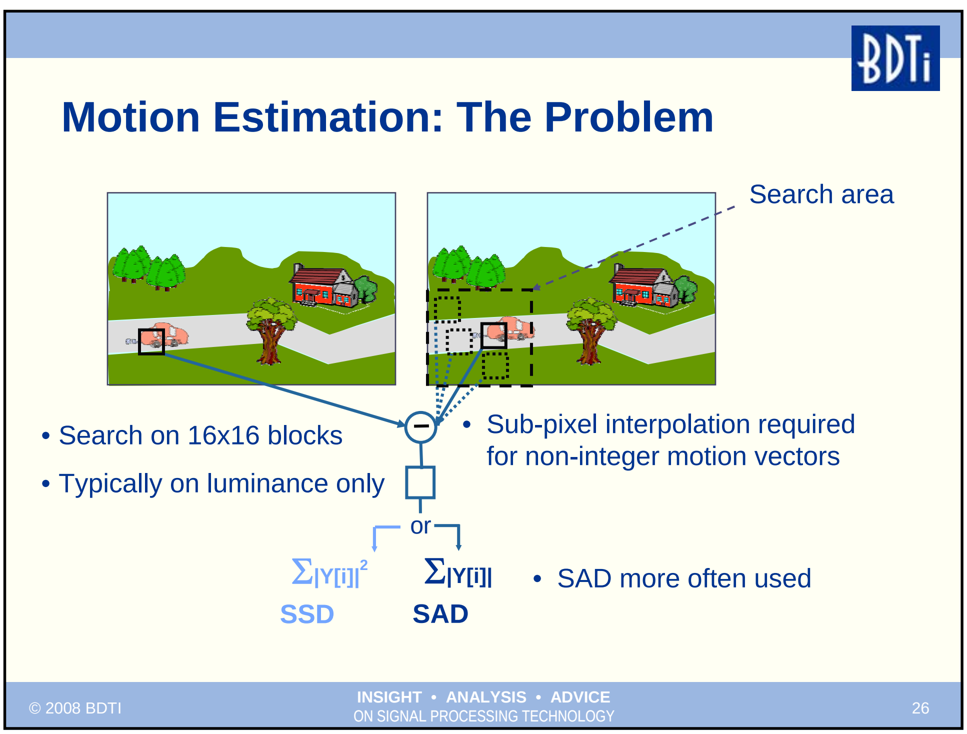
Motion Estimation: The Problem
Search area
• Search on 16x16 blocks
• Typically on luminance only
• Sub-pixel interpolation required for non-integer motion vectors
or
Σ|Y[i]|²
SSD
Σ|Y[i]|
SAD
• SAD more often used
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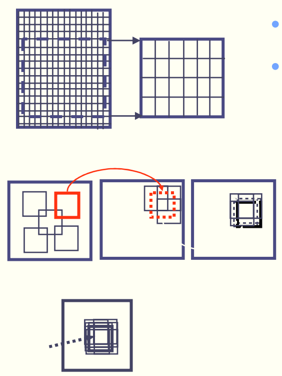
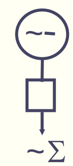
Efficient Motion Vector Search



- Exhaustive search is impractical
- Evaluate only promising candidate motion vectors
  - Don't have to find absolute best match
    - Trade video quality for computational load
  - Many methods in use
    - Often proprietary
    - Refine candidate vector selection in stages
    - Predict candidate vectors from surrounding macroblocks and/or previous frames



Motion vector search approach is a key differentiator between video encoder implementations

Motion Estimation: Processing Reqt's

Compute load
- Most demanding task in video compression
  - Up to 80% of total encoder processor cycles
  - Many search methods exist, with varying requirements
  - May vary with video program content
  - Makes encoder computational demand several times greater than that of the decoder
  - Dominated by SAD computation

Memory use
- Motion estimation requires reference frame buffers
  - Frame buffers dominate memory requirements of encoder
  - E.g., 152,064 bytes per frame @ CIF (352x288) resolution
- High memory bandwidth required

Motion Compensation: Processing Reqt's

Motion compensation copies pixels from reference frame to predict current macroblock
- Requires interpolation for non-integer motion vector values

Compute load
- Varies with video program content
- Can require from 5% to 40% of total decoder processor cycles
- MPEG-4 CIF (352x288) @ 30 fps:
  - Roughly 15-25 MHz on a TMS320C55x DSP (estimated)

Memory usage
- Requires reference frame buffers
  - Frame buffers dominate decoder memory requirements
- Good memory bandwidth is desirable, but less critical compared to motion estimation

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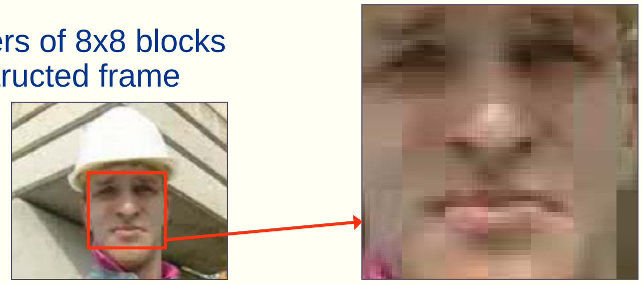
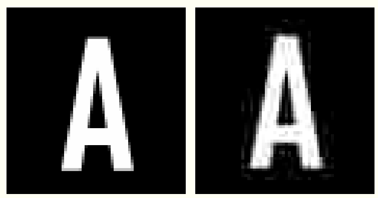
Artifacts: Blocking and Ringing

Blocking: Borders of 8x8 blocks visible in reconstructed frame



Ringing: Distortions near edges of image features

Original image



Reconstructed image (with ringing Artifacts)

Deblocking and Deringing Filters

Low-pass filters are used to smooth the image where artifacts occur

Deblocking:

- Low-pass filter the pixels at borders of 8x8 blocks
- One-dimensional filter applied perpendicular to 8x8 block borders

Deringing:

- Detect edges of image features
- Adaptively apply 2D filter to smooth out areas near edges
- Little or no filtering applied to edge pixels in order to avoid blurring

Artifact Reduction: Deblocking

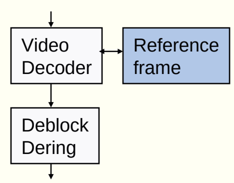
Original MPEG Still Frame

Horizontally & Vertically Deblocked Still Frame

Post-processing vs. In-loop

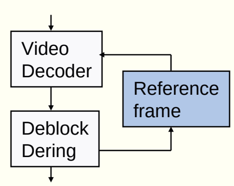
Deblocking/deringing often applied after the decoder (post-processing)

- Reference frames are not filtered
- Developers free to select best filters for the application or not filter at all



Deblocking/deringing can be incorporated in the compression algorithm (in-loop filtering)

- Reference frames are filtered
- Same filters must be applied in encoder and decoder
- Better image quality at very low bit-rates



Artifact Reduction: Processing Reqt's

Deblocking and deringing filters can require more processor cycles than the video decoder

- Example: MPEG-4 Simple Profile, Level 1 (176x144, 15 fps) decoding requires 14 MIPS on ARM's ARM9E for a relatively complex video sequence
- With deblocking and deringing added, load increases to 39 MIPS
  - Nearly 3x increase compared to MPEG-4 decoding alone!

Post-processing may require an additional frame buffer

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Color Space Conversion

Need for color conversion
- Capture and display video equipment: RGB...
- ...while codecs use YUV

Computational demand
- 12 operations per pixel → 36 million operations/second for CIF (352x288) @ 30 fps
  - About 36 MHz on a TMS320C55x DSP
  - Not including interpolation of chrominance planes
- Roughly 1/3 to 2/3 as many processor cycles as the video decoder

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Challenges in Evaluating Solutions

Validate the production-readiness of the solution

Measuring performance fairly
- Algorithm configurations
- Test streams
- Test conditions
- Performance metrics

Vendor data often provides little help
- Apples-to-apples comparisons are difficult
- Varying and often unrealistic configurations, test streams, test conditions, and metrics

BDTI's Approach

Standardization:
- Operating points (codec parameters)
- Test streams
- Metrics
- Instrumentation guidelines

Independent verification of:
- Functionality
- Performance
- Metrics used for comparisons

BDTI H.264 Decoder Solution Benchmarking

Primary operating point:

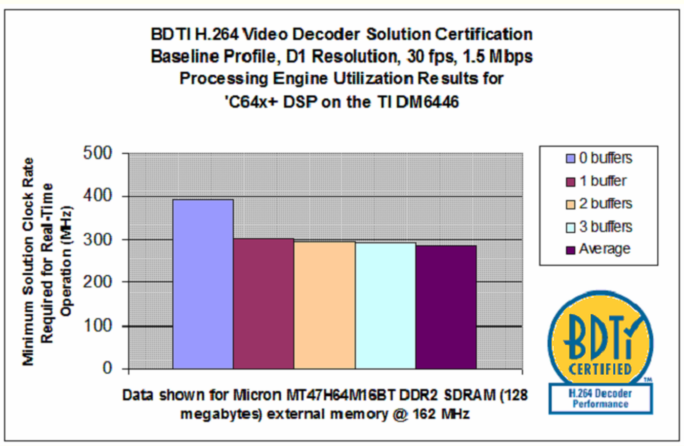
- Baseline profile
- D1 resolution (720 × 480)
- 30 frames per second
- 1.5 Mbit/second test stream ***(proprietary)***

Other "secondary" operating points are characterized to provide a complete performance picture

Metrics:

- CPU utilization
- External memory bandwidth utilization
- Energy consumption (mJ/frame)
- Die area or cost (mm² or $)
- Program and data memory use (Mbytes)

Example Results: H.264 on TI TMS320DM6446



For more results, see www.BDTI.com

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- Comparing performance and efficiency
- **Conclusions**

Conclusions

Understanding the computational and memory requirements of video compression is critical but challenging

- Application design choices are driven by computational and memory requirements
  - Algorithm selection, processor selection, software optimization
  - Video processing often stresses processing resources
- But video applications combine many different signal-processing techniques
  - Transforms, prediction, quantization, entropy coding, image filtering, etc.
- And there is large variation in computational and memory requirements among different applications
  - E.g., digital camcorder has vastly different requirements from a video-enabled cell phone, even when using the same compression standard

Conclusions, cont.

Understanding computational load
- Computational load of encoder is several times greater than that of decoder due to motion estimation
- Computational load proportional to frame size and rate for most functions
  - Note: VLD computational load is proportional to bit rate
- Post-processing steps—deblocking, deringing, color space conversion—add considerably to the computational load

Computational load can be difficult to predict
- Many different approaches to motion estimation
- Computational load of some tasks can fluctuate wildly depending on video program content
  - E.g., motion compensation

Conclusions, cont.

Understanding memory requirements:
- Memory requirements dominated by frame buffers
  - A decoder that supports only I and P frames requires two frame buffers (current and reference)
  - A decoder that supports I, P, and B frames requires three buffers (current and two reference)
  - Deblocking/deringing/color conversion may require an additional buffer
- Program memory, tables, other data comprise a non-negligible portion of memory use
  - But this portion is still several times smaller than frame buffers

High memory use often necessitates off-chip memory
- Off-chip memory bandwidth can be a performance bottleneck

Conclusions, cont.

Video compression used in many products
- DVDs, digital TV, personal video recorders, Internet video, multimedia jukeboxes, video-capable cell phones and PDAs, camcorders…

Different products have different needs
- Wide range of frame sizes and rates, video quality, bit rates, post-processing options, etc.
- Result in wide range of computational and memory requirements

Need to understand the operation of video codecs
- To understand computational and memory requirements
- To select codecs, processors, software modules
- To optimize software

Need to compare performance and efficiency of competing solutions
- Requires a thoughtful approach: algorithm variants, test data, metrics, …

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For More (Free!) Information…
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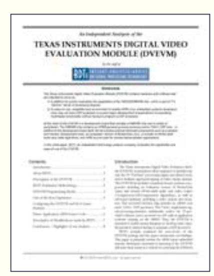
www.InsideDSP.com



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benchmark scores for dozens of processors, FPGAs, video solutions, etc.

Pocket Guide to Processors for DSP
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Articles, white papers, and presentation slides
- Processor architectures and performance
- Signal processing applications
- Signal processing software optimization

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