Compression of Video Signals

Basic Concepts and Some Recent Advances in the Field

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Outline

1. Introduction
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   - Structure of a hybrid DCT+DPCM coder
   - Today's standards-based and proprietary algorithms
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2. Basic Concepts and Techniques
   - DPCM, Motion compensation
   - Transform - based coding
   - Quantization
   - Noiseless coding
3. Conclusions

A Bit of History

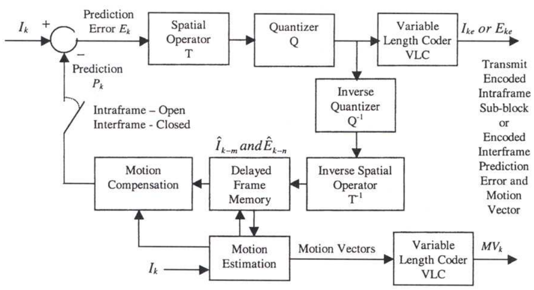
1. First techniques for coding of signals:
   - PCM (Reeves, 1938)
   - Delta-modulation (Deloraine, 1946)
   - DPCM (Cutlet, 1952)
2. Transforms
   - KLT (Karhunen & Loeve, 1948)
   - DFT $\sim$ KLT! (Pearl, 1973)
3. Intra-frame image/video coding
   - DCT (Ahmed, Natarajan, Rao, 1974)
4. Simple frame-difference coding (DPCM, scalar quantizer)
   - H.120 (1984)

A Bit of History (Cont'd)

5. First successful hybrid DPCM/DCT scheme
   - H.261 (1991)
     - motion compensation
6. Incremental improvements:
   - MPEG-1 (1993), MPEG-2/H.262 (1994)
     - 1/2-pixel motion compensation
   - H.263 (1996)
     - block-size adaptive motion compensation
   - H.26L (1999) $\rightarrow$ MPEG-4 AVC/H.264
     - 4x4 integer transforms
     - 1/4-pixel motion compensation
     - improved entropy coding

Structure of DPCM/DCT Codecs

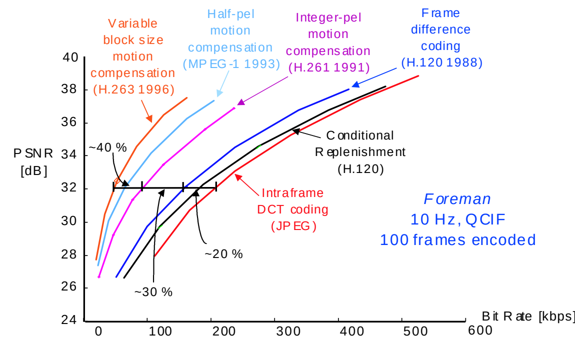
- Generalized structure (H.261,H.263,MPEG-1,2):



- Notation:
  - I_k – k-th input frame
  - P_k – predictor constructed using previous reconstructed frames $\hat{I}_{k-1} \ldots \hat{I}_{k-m}$
  - $E_k = I_k - P_k$ – prediction residual
  - $\hat{E}_k$ – reconstructed prediction residual

Pace of the Progress

- Performance of video codecs is improving by 0.5 dB every 12 to 18 months
  - B. Girod (1998)



- Performance metrics
  - I, $\hat{I}$ – original/reconstructed images, containing $m \times n$ pixels, of d bits each;
  - $MSE = \frac{1}{m\,n} \sum_{i=1}^{m} \sum_{j=1}^{n} \left(I_{i,j} - \hat{I}_{i,j}\right)^2$;
  - $PSNR = 20 \log_{10} \left(\frac{2^d}{\sqrt{MSE}}\right)$

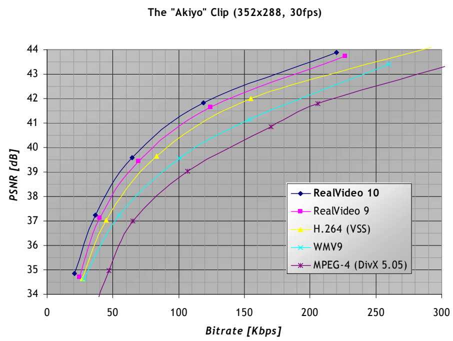
Key Improvements Since H.261:

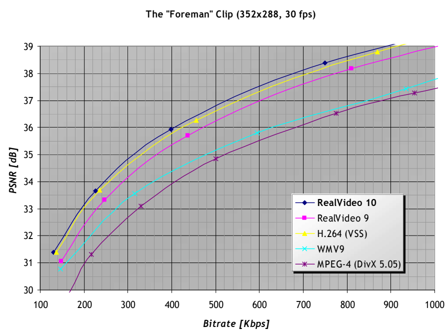
1. Half-pixel accurate motion compensation
   - +1.0..1.5dB gain (QCIF, 10Hz, 100Kbps)
   - introduced in MPEG-1 (1993)
2. Block-size adaptive motion compensation
   - +0.5..1.5dB gain (QCIF, 10Hz, 100Kbps)
   - introduced in H.263(Annex F) (1996)
3. 1/4-pixel-accurate motion compensation
   - +0.5..1.0dB gain (CIF, 24Hz, 1000Kbps)
   - proposed in MPEG-4 (ACE-profile) (1999)
   - different scheme in H.264/MPEG-4 AVC (2001)
4. 4x4 integer transforms + improved compander
   - +0.5..1.5dB gain (QCIF, 10Hz, 100Kbps)
   - introduced in H.26L (1999), improved in H.264/MPEG-4 AVC (2001).
5. Improved entropy coding schemes
   - 15-25% bitrate reduction (QCIF, 10Hz, 36dB)
   - first realized in RealVideo 8 (1999)
   - different schemes H.264/MPEG-4 AVC (2001)

Current Algorithms

- Standards-based:
  - MPEG-4 AVC / H.264 codecs (2003)
    - derivatives of the H.26L project (1999)
  - MPEG-4 (original version, 2001)
    - derivative of MPEG-2, H.263
    - not quite competitive these days
- Proprietary:
  - RealVideo 10 – RealNetworks
  - WMV 9 – Microsoft
  - VP6 – On2
- MPEG-4 wrapped in proprietary formats:
  - DivX, XdiV

Current Algorithms (RD-Plots)





Basic Concepts and Techniques

- Basic techniques:
  1. Predictive coding
     - Linear prediction
     - Motion compensation
  2. Transform - based coding
  3. Quantization
     - RD-theory
     - Direct vs. Successive quantization
  4. Noiseless coding
     - Coding of known sources
     - Universal coding

(items 1–3: skipped)

Noiseless Coding (Overview)

- Consider the following:

  $A = \{a, b, c\}$ - alphabet, $|A| = 3$

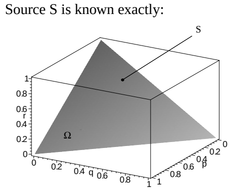
  Ω - a class of memoryless sources over A;

  $\Pr(a) = p$; $\Pr(b) = q$; $\Pr(c) = r$; $(p+q+r = 1)$

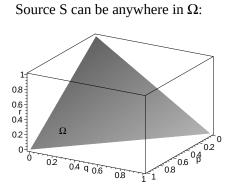
  $S \in \Omega$ - source to be encoded.

- Types of problems in noiseless coding:

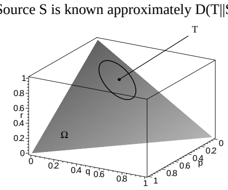
Source S is known exactly:



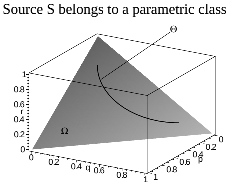
Source S can be anywhere in Ω:



Source S is known approximately D(T||S) < δ:



Source S belongs to a parametric class Θ:



Noiseless Coding (Definitions)

- We have the following:
  - $S \in \Omega$ - known memoryless source:

    $$P_S(\alpha) := \Pr(S \rightsquigarrow \alpha);$$

  - w – a word $|w| = n$ produced by S:

    $$P_S(w) = \prod_{\alpha \in A} P_S(\alpha)^{r_\alpha(w)},$$

    where $r_\alpha(w)$ denotes the number of letters α in w. Indeed: $\sum_{\alpha \in A} r_\alpha(w) = |w|$.
  - A **block code** ϕ:

    $$\phi : A^n \to \{0, 1\}^*$$

    where the output set is *decipherable*.

- Key parameters:
  - The **entropy** of source S:

    $$H(S) = -\sum_{\alpha \in A} P_S(\alpha) \log P_S(\alpha).$$

  - The **average cost** of code ϕ:

    $$C(\phi, n, S) = \frac{1}{n} \sum_{w \in A^n} P_S(w) |\phi(w)|.$$

  - The **average redundancy**:

    $$R(\phi, n, S) = C(\phi, n, S) - H(S).$$

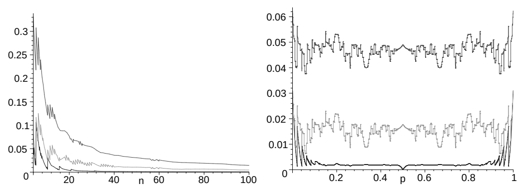
Noiseless Coding (Known Source)

- Redundancy rate decreases with n as:

$$R(\phi_S, n, S) = \frac{C}{n}$$

where C is a constant.

- Examples ($A = \{0, 1\}$, $\log_2 \frac{\Pr(1)}{\Pr(0)}$ is irrational):
  - Shannon code: $C_S = 1/2 + o(1)$
  - Huffman code: $C_H = 3/2 - 1/\ln 2 + o(1) \approx 0.0573..$
  - Gilbert-Moore code: $C_{GM} = 3/2 + o(1)$.



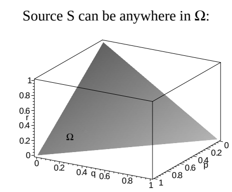
Average redundancy rates of Gilbert-Moore, Shannon, and Huffman block codes (left: fixed source $\Pr(0) = 1/8$; right: fixed block $n = 32$, $p = \Pr(0)$).

Noiseless Coding (Unknown Source)

- We know only that $S \in \Omega$

- The solution is to find a code ϕ_Ω:

$$R(\phi_\Omega, n, \Omega) = \inf_{\phi \in \Phi} \sup_{S \in \Omega} R(\phi, n, S) \ .$$



- The code ϕ_Ω is called a **universal block code** for a class of sources Ω.

- Achievable redundancy rate (Krichevsky,1975):

$$R(\phi_\Omega, n, \Omega) = \frac{1}{n}\left[\frac{|A|-1}{2}\log n + C\right] = O\left(\frac{\log n}{n}\right)$$

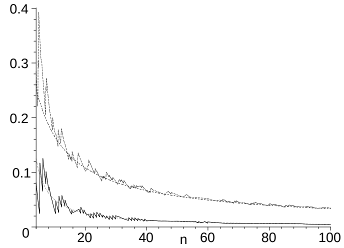
which is slower than $O\left(\frac{1}{n}\right)$ convergence rate of codes for known sources.

Noiseless Coding (Comparison)

- Again, if the source S is known exactly, then the redundancy of its optimal encoding is decreasing as: $R \sim \frac{C}{n}$,

- but if we only know that the source is memoryless, we attain: $R \sim C\ \frac{\log n}{n}$.

- Example:



Block Shannon code vs. universal code under a binary source with $\Pr(0) = 1/8$.

Noiseless Coding (Construction)

- Construction of universal codes:
  - probability estimation + encoding

- Block encoding can be done by either:
  - Arithmetic encoders (Rissanen, Pasco, 1976)
  - Enumerative codes (Lynch, Davisson, 1966, Babkin, Shtarkov, 1968-74, . . .)

- Probability estimators:
  - Laplace estimator:

$$P_L(w) = (m-1)!\frac{r_{\alpha_1}(w)! \dots r_{\alpha_m}(w)!}{(|w| + m - 1)!},$$

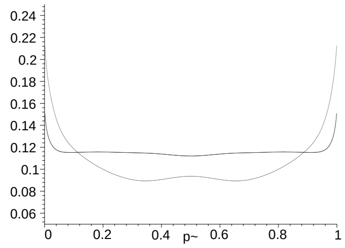
  - Krichevsky-Trofimov (KT) estimator:

$$P_{KT}(w) = \frac{\Gamma(m/2)}{\Gamma(1/2)^m}\frac{\prod_{\alpha \in A}\Gamma(r_\alpha(w) + 1/2)}{\Gamma(|w| + m/2)},$$

where m is cardinality of the alphabet A, $r_\alpha(w)$ - frequencies of symbols in a word w, and $\Gamma(x)$ is the Γ-function.

Noiseless Coding (Estimation)

- Performance of KT vs. Laplace estimators:



Redundancy rates of block universal codes under a binary source with Pr(0) $= p$. Block size $n = 32$.

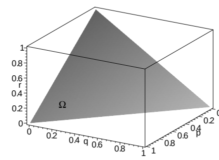
- KT-estimator achieves uniform convergence on Ω.

- Both estimators can be implemented in an incremental fashion; e.g.:

$$P_L\,(w\,\alpha) = P_L\,(w)\,\frac{r_\alpha(w)+1}{|w|+m}\,.$$

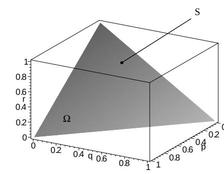
Noiseless Coding (Other cases)

Source S can be anywhere in Ω:



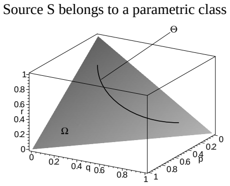
$$R \sim \frac{|A|-1}{2\,n}\log n\,;$$

Known sample of length l produced by S:



$$R \sim \frac{|A|-1}{2\,n}\log\frac{n+\ell}{\ell}\,;$$

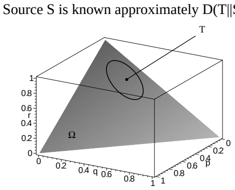
Source S belongs to a parametric class Θ:



$$R \sim \frac{d}{2\,n}\log n\,;$$

when $\Theta \subset \mathbb{R}^d$

Source S is known approximately D(T||S) < δ:



$$R \sim \frac{|A|-1}{2\,n}\log\,(n\,2\,\delta)\,;$$

References

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Questions?