Introduction to Multiple-Description Coding

a Joint Source-Channel Coding Paradigm with a Twist Towards Digital TV

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Appetizer - Candy for the Ear & Sweets for the Mind

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- Or should we???

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- Each pixel color is represented by at least 8 bits, and there are three color components Red, Green, and Blue

$$\text{SDTV} \quad 720 \times 576 \times 25 \times 3 \times 8 \approx 248 \text{ Mbits/sec}$$

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- Let’s face it — we need video compression!

Lossy Image Compression - Source Coding

- 8 bit gray-scale image 512 $\times$ 512 pixel: Bit-rate is 2 Mbit

Lossy Image Compression - Source Coding

- Represent the image by the MSB: Bit-rate is 0.25 Mbit

Lossy Image Compression - Source Coding

- Represent the image by the two MSB's: Bit-rate is 0.5 Mbit

Lossy Image Compression - Source Coding

- Coded using JPEG: Bit-rate is 0.1 Mbit $\approx$ 0.38 bits/pixel

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Compression for Storage and Retrieval not Streaming

- MP3, JPEG, MPEG2, MPEG4, etc. are meant for storage and retrieval of audio, images, and video
- Long delay (allowed to work on the entire audio or video file)
- Are these compression formats suitable for real-time streaming?
- Not if there's gonna be varying delay, varying bandwidth, packet losses

(recall poor Clapton?)

Outline

1. Introduction to Compression
   - Motivation for Compression
2. Compression Meets the Network
   - Coding without Network Awareness
   - Coding with Network Awareness
3. Multiple-Description Coding
   - Theory
   - Practice
4. Conclusions

What if the Network is not Ideal?

- Packet loss concealment
- Use back-channel (feedback) and request lost packets
- Channel Coding
- Hybrid ARQ
- Link Layer Adaptation
- Multi Resolution Coding

- *Analogue Coding, Space-Time Coding, Super Position Coding (Onion Peeling), Coset Coding*

- Multiple-Description Coding

Packet loss concealment

- Replace the lost packet by “something clever”

1) Repeat previous packet (GSM)
2) Extrapolate from previous packet (hard to do)
3) Wait for next packet and interpolate

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In digital tv in Europe: Mute sound and freeze picture!

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- Pros & Cons:

+ Does not cost any additional bits (done at the decoder)
- Usually requires a delay to work well
- Often hard to make a good substitution
- Doesn’t work for consecutive packet droppings

Feedback Channel

- Makes it possible to request lost or broken packets

- Pros & Cons:

+ Only need additional bits when there is a packet loss
- Requires at least a round trip delay (before arrival of the retransmitted packet)
- The retransmitted packet and the request may be lost
- In many “real-time” applications, delayed packets are often treated as being lost
- Does not work well in broadcast environments due to the feedback implosion problem
(loss of a single packet – leads to multiple requests)

Channel Coding

- In packet-switched networks (e.g., the Internet), packets are generally received error-free or not received at all
- Packet losses are mainly due to router congestions

- Forward Error Correction (FEC) Coding:
  Adds redundancy to combat channel “noise”
  —Parity Check Codes, (Hamming and Reed-Solomon)

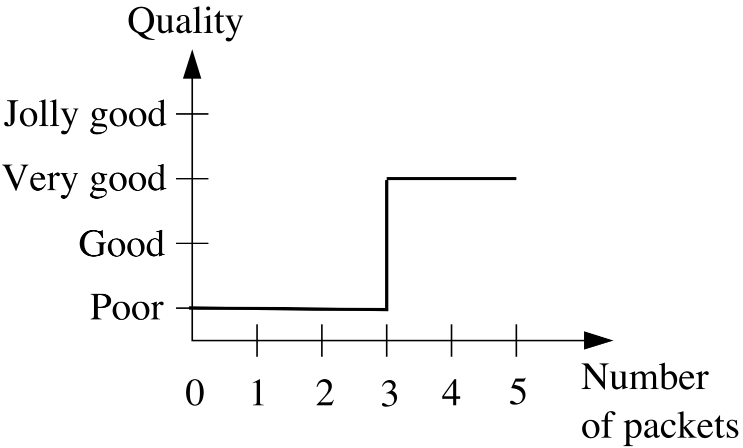
- Pros & Cons:

+ Does not need a back channel
- Severely increases the overall bit rate: Conservative
  —sender does not know the current channel conditions
- Usually requires a few packets delay to be efficient

Channel Coding (how does it work)

- (n, k) FEC erasure codes: $(n > k)$
- Takes k packets as input and outputs n packets
- An $(n, 1)$ erasure code is also called a repetition code
- On reception of less than k packets, the receiver cannot decode at all
- On reception of any k packets, the receiver can completely recover the original k packets
- On reception of more than k packets, there is no quality improvement
- Cliff-wall effect

Cliff-Wall Effect of a $(5,3)$ Erasure Code



- This is todays digital TV in Denmark!

Hybrid ARQ

- Partial use of error correcting codes and partial use of feedback
- Automatic Repeat reQuest (ARQ), re-transmit only lost packets, which cannot be recovered

- Pros & Cons:

\+ Works better than ARQ and ECC alone

+/- Smaller increase in bit-rate than for ECC

+/- Requires a feedback channel but less often than ARQ

\- Hard to find optimal trade-off

Link Layer Adaptation

- Utilizes erasure codes and a back-channel
- Predicts channel conditions for future transmissions
- Trade off bit-budget between source and channel coding
- If the channel will be poor, a strong (high bit-rate) channel coder and a weak (low bit-rate) source coder are used
- If the channel will be good, a high bit-rate source coder and a weak channel coder are used
- Example: AMR Speech Coder for GSM has bit rates of 12.2, 10.2, 7.95, 7.40, 6.70, 5.90, 5.15, and 4.75 kbit/sec. and the total bit rate after channel coding is 22.8 kbit/sec.

Link Layer Adaptation

- Pros & Cons:

+ The overhead is reduced a lot compared to FEC
—the channel condition is (partially) known at the sender
+ Possible to optimize the trade-off between source and channel coding (joint source-channel coding)
- Requires a system that is capable of (accurately) predicting the future channel conditions
- Requires a back channel (perhaps not from receiver)
- The channel must be slowly varying
- Does not work for multicast or broadcast since it is unlikely that all end-users experience identical channel conditions

Multi-Resolution Coding

- Falls under the category of scalable coding
- The signal is encoded into a base layer and a refinement layer
- The base layer yields tolerable audio/video quality
- The refinement layer is no good by itself
- Base + refinement layers ⇒ quality improvement
- Pros & Cons:

+ Allows for “online” quality scalability in a network

\- Requires prioritized networks, “smart” routers, or dedicated “refinement” channels
—everyone needs the base layer
—and only some the refinement layer!

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2) if two individual descriptions are both good
   —they must both “look” a lot like the source
   —thus, they “look” a lot like each other
   —hence, they cannot refine each other very well!

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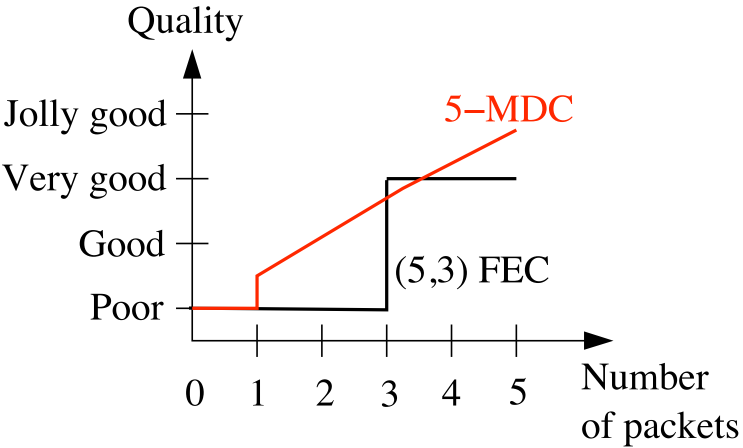
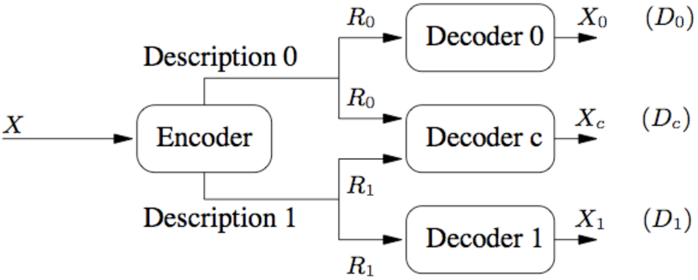
3) Vice versa, if their joint description is good
   —at least one of the individual descriptions must be poor!

Motivation for MDC: No Cliff-Wall Effect!



Two-Channel Multiple-Description Coding



- With MDC — we ask the following questions:

1) What are the information theoretic R-D limits?
2) How do we approach these limits in practice?

The MD RDF Quadratic Gaussian (Memoryless)

- $R_0 \geq I(X;X_0) = R(D_0) = \frac{1}{2}\log_2(\sigma_X^2/D_0)$

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- $R_0 + R_1 \geq I(X; X_0) + I(X; X_1) + I(X_0; X_1)$

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- $R_0 + R_1 \geq I(X;X_0) + I(X;X_1) + I(X_0;X_1)$
  $= R(D_c) + \frac{1}{2}\log_2(\gamma) = \frac{1}{2}\log_2(\sigma_X^2/D_c) + \frac{1}{2}\log_2(\gamma)$

where

$$\gamma = \begin{cases} \mathbf{1}, & \boldsymbol{D_c < D_0 + D_1 - \sigma_X^2} \\ \frac{\sigma_X^2 D_c}{D_0 D_1}, & D_c > \left(\frac{1}{D_0} + \frac{1}{D_1} - \frac{1}{\sigma_X^2}\right)^{-1} \\ \frac{(\sigma_X^2 - D_c)^2}{(\sigma_X^2 - D_c)^2 - \left(\sqrt{(\sigma_X^2 - D_0)(\sigma_X^2 - D_1)} - \sqrt{(D_0 - D_c)(D_1 - D_c)}\right)^2}, & \text{o.w.,} \end{cases}$$

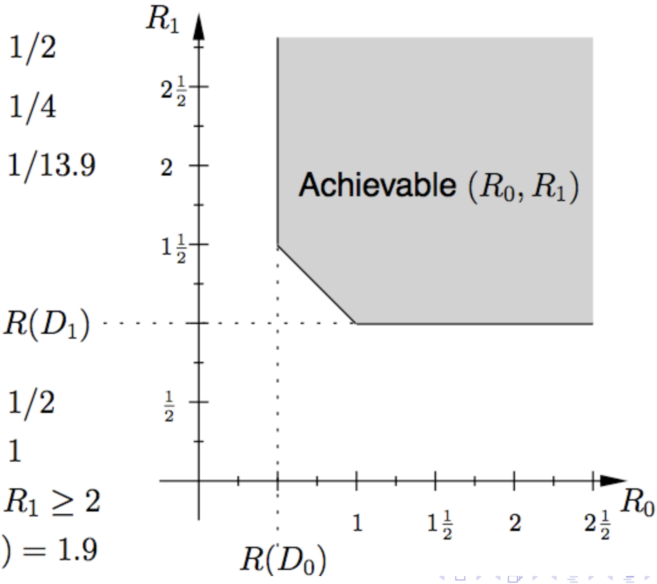
[Ozarow'80, Chen et al.'06]

MD Rate-Rate Region (Quadratic Gaussian)

$D_0 = 1/2$

$D_1 = 1/4$

$D_c = 1/13.9$



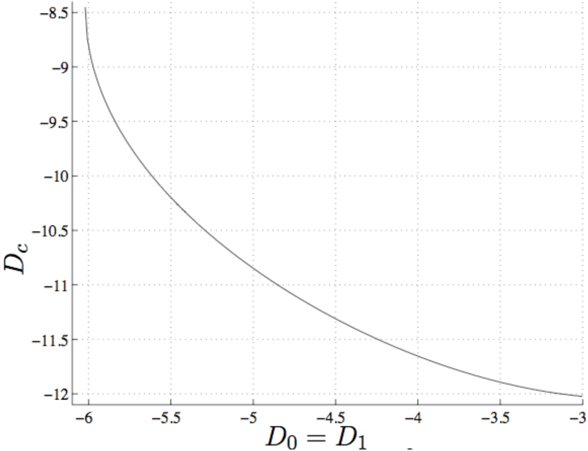
$R_0 \geq 1/2$

$R_1 \geq 1$

$R_0 + R_1 \geq 2$

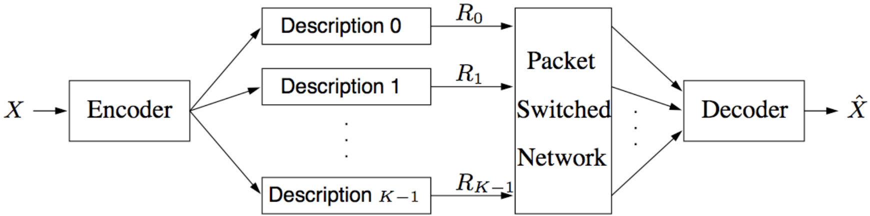
$R(D_c) = 1.9$

MD Distortion-Distortion Function (Q. Gaussian)



$R_0 = R_1 = 1$ bit/dimension. X is unit-variance and i.i.d. Gaussian.

Multiple-Description Coding for Many Descriptions



- Encode X into K descriptions
- Send descriptions over lossy network
- Distortion depends upon which descriptions are received
- Descriptions refine each other
- Very much an open problem in general

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Practical Constructions of Multiple Description Codes

- The simple engineering approach:

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Base layer	Refinement

2) **Duplicate the base layer**

Description 1 | Base layer

Description 2 | Base layer

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2) **Duplicate the base layer**

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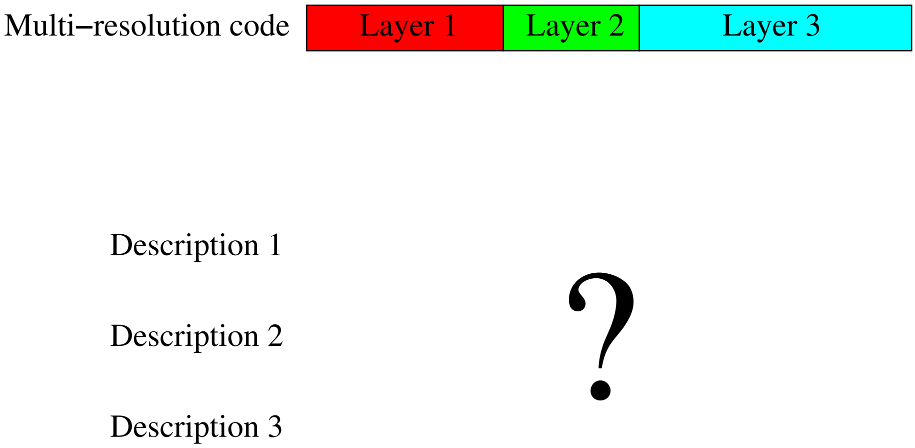
3) **Split the refinement layer into two parts**

Description 1 | Base layer | Refine

Description 2 | Base layer | ment

Practical Constructions of Multiple Description Codes



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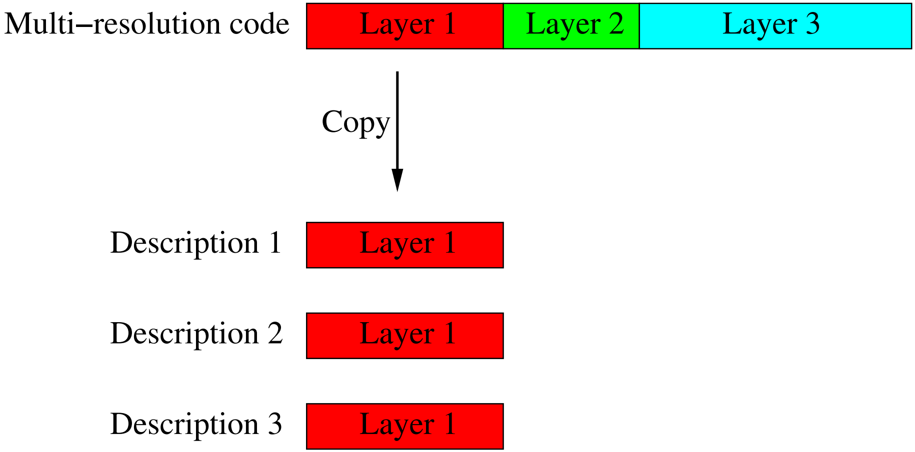

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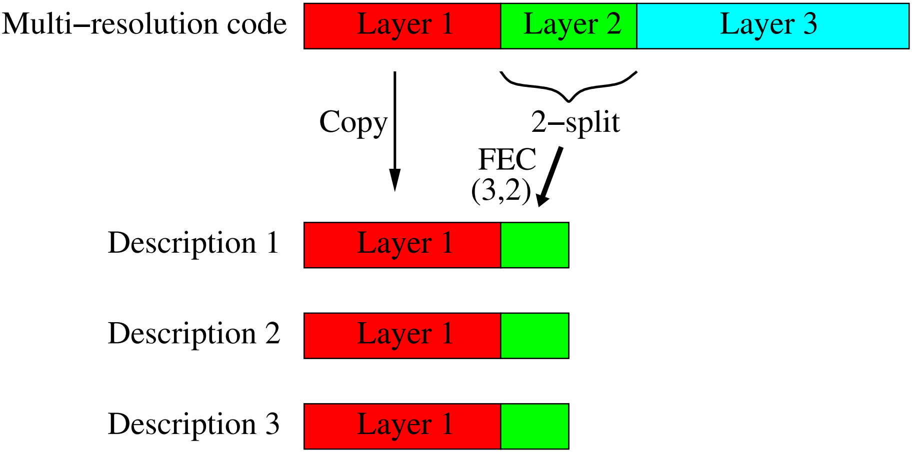

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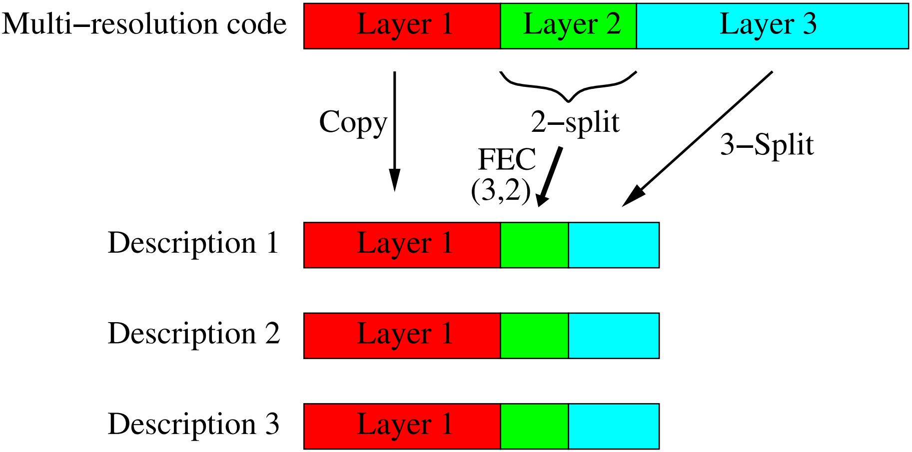


Practical Constructions of Multiple Description Codes

- The h.264 MPEG AVC (advanced video coding) standard used in digital TV, has recently been generalized to include scalable coding: h.264 MPEG SVC (scalable video coding)
- Thus, one can create a *prioritized* layered video stream, which by use of FEC's can be turned into an *unprioritized* multiple-description stream
- The h.264 AVC and h.264 SVC are both available for free online (C++ implementation)
- Erasure codes are also available standard components

Practical Constructions of Multiple Description Codes

- Erasure codes (FEC)
- Index-assignments (Ph.D. work)
- Quantization splitting
- Correlating transforms
- Frame expansions
- Redundant filterbanks
- Compressed Sensing
- ℓ_1-Compression (Tobias L. Jensen)
- Oversampling and Delta-Sigma Quantization

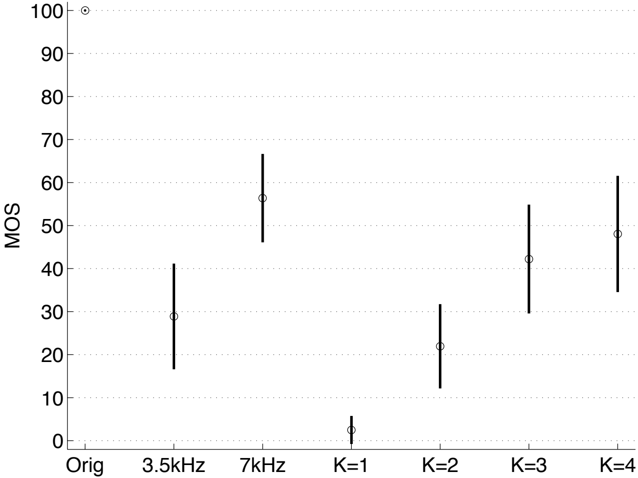
Back to the real-time streaming question

- We developed a transform coder, which resemble mp3 (MPEG-2 AAC)
- Sampling frequency of music is 48 kHz (mono)
- The coder is block based, each block beeing approx 20 ms. (1024 samples)
- We use multiple description coding: 1 to 4 descriptions
- Total target bit-rate is 96 kbit/sec. (2 bits/sample)

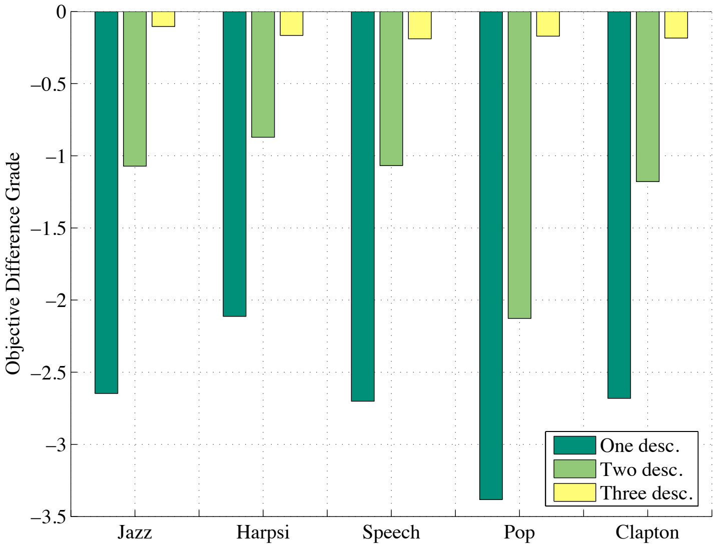
1 desc.	2 desc.	3 desc.	4 desc.
96 kbps	48 kpbs	32 kpbs	24 kbps

- The packet loss probability is 30%
- The losses are i.i.d.

30 % i.i.d. Packet losses (Eric Clapton) - MUSHRA



Objective Difference Grade



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- **Tomorrow:**

— The Anillo Project —

joint source-channel coding and ***control***