Robust Source Coding

Bastiaan Kleijn
KTH School of Electrical Engineering
Stockholm

Overview

- Motivation for robust coding technologies
- Motivation / technology overview
- FEC and Multiple description coding

High Quality Now Less Natural

- Conventional circuit-switched networks
  – Virtually no bit errors, no loss
- Mobile networks
  – Reasonable cost implies bit errors
- Packet networks
  – Reasonable cost implies packet loss

Networks More Diverse

- How it was:
  - Single-paradigm network end-to-end
  - One service
- How it is:
  - Many paradigms in one composite network:
    - Circuit-switched network
    - Packet network
    - Wireless circuit-switched network
    - Wireless packet network
  - Many types of service
    - Range of quality-cost
    - Streaming versus one-on-one communication

Basic Technologies

- Bit-error correction
  - Established technology
  - Add redundancy
    - Parity bits
    - Reed-Solomon code

- Packet-loss recovery
  - *New* technology
  - Forward error correction (erasure codes)
  - Multiple-description coding
  - Packet-loss concealment

Packet-Loss Recovery

- Transmitter-based technologies
  - Automatic repeat request
  - Forward error correction (FEC)
  - Multiple description coding (MDC)
  - Layered coding
  - Interleaving

- Receiver-based technologies
  - Insertion
  - Interpolation
  - Regeneration

Note: traditionally robustification sits in the physical and in the transport (fourth) layer of OSI model; we like it to sit in the application layer; cross-layer interaction?

Media-Specific FEC

- Redundancy added to the bit stream to counter bit errors and packet loss
- Redundancy added at “coding unit” level
- Examples
  - Low-rate coder added to the bit stream
  - Repeat of sections of key portions of coded data (H.263+)
- Low complexity
- Low latency
- Designer selects where to add redundancy
- Loss of quality when packet is lost
- Generally heuristic, but same idea as MDC
  - No problems with feedback in system

Media-Independent FEC

- Add redundancy to *bit stream*:
  - Reconstruct perfectly up to certain loss rate
  - Catastrophic failure beyond that error rate
    - Not flexible
- Examples
  - XOR
  - Reed Solomon
- Based on mathematics of finite fields
  - Rigorous

Multiple Description Coding (MDC)

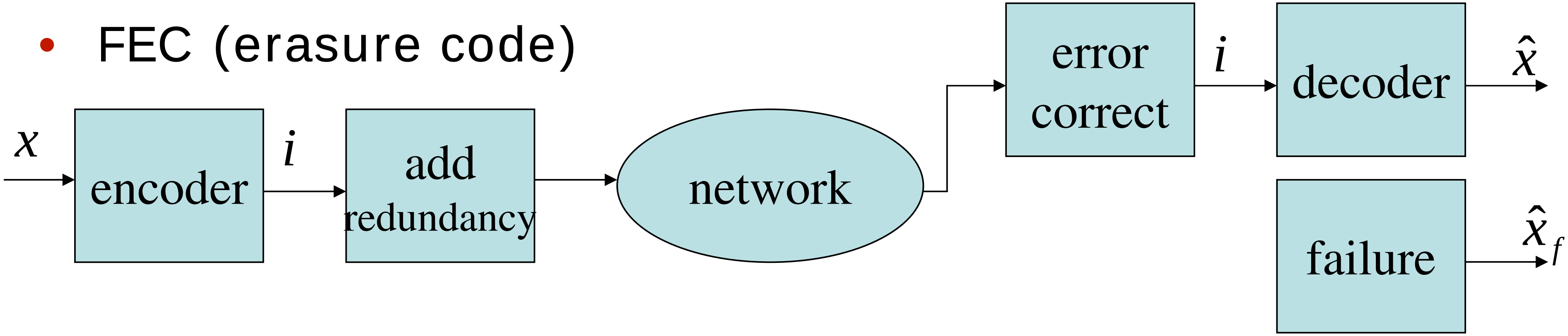
- Transmit multiple descriptions
  - Optimize encoders to maximize expected performance with loss rate of channel
- Many decoders
  - Example: two-descriptions A and B
    - Decoder for A
    - Decoder for B
    - Decoder for A and B
- Operates on quantizer level / rooted in math

FEC versus MDC

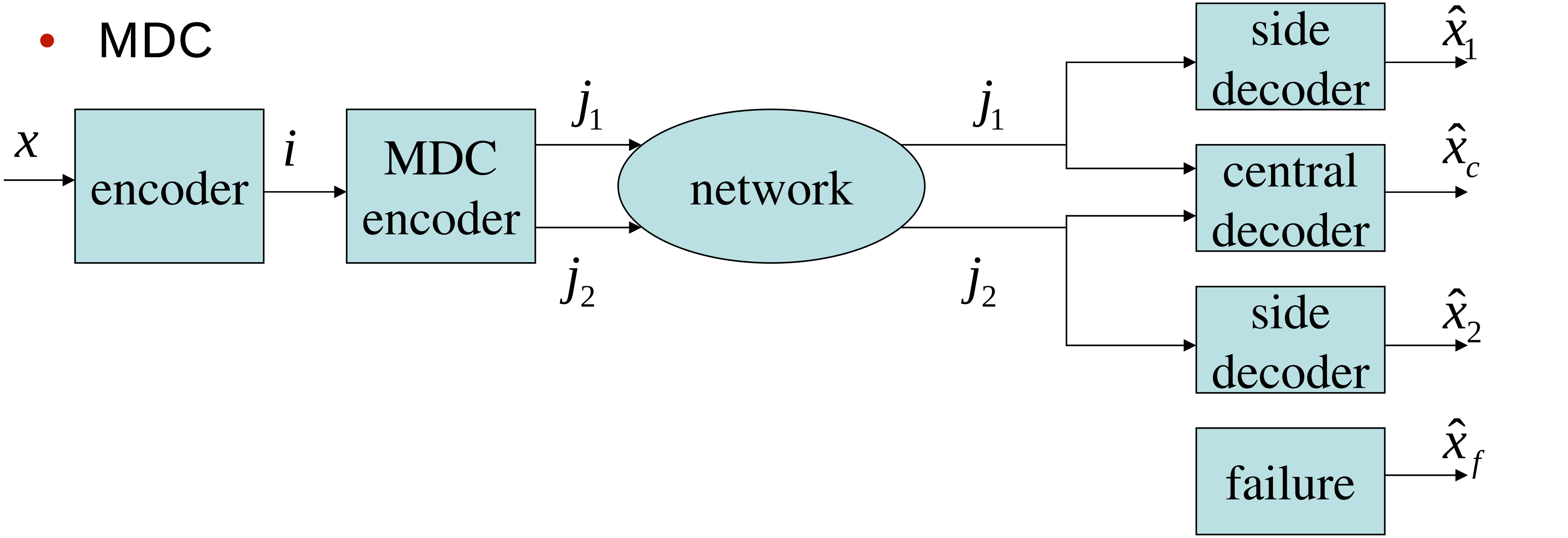
- FEC operates on bit stream
  - Distortion measure irrelevant
  - Catastrophic failure
  - Convenient for legacy coders
- MDC operates on source
  - Minimizes distortion measure
  - Multiple decoding quality levels
  - Requires redesign of coder
- Conclusion: MDC should be better but requires redesign

FEC versus MDC

- FEC (erasure code)

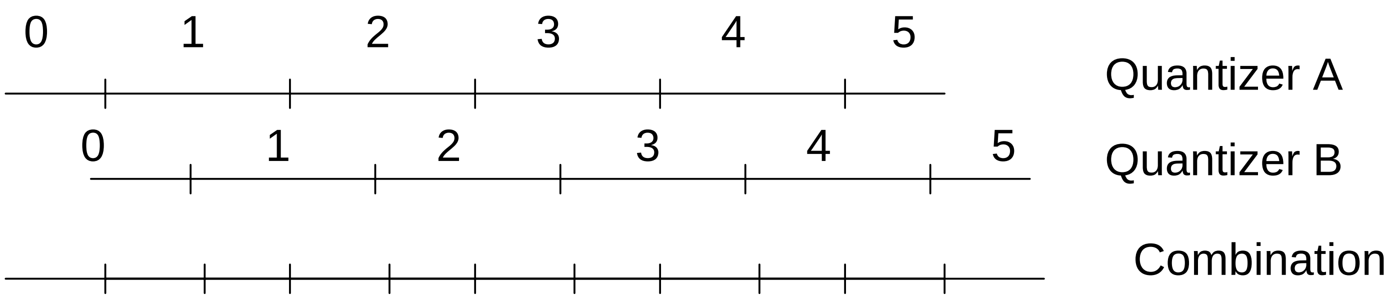


- MDC



Simple MDC *Scalar* Quantizer

- Consider a CE quantizer with $D = \sigma 2^{-\frac{r}{k}H(I)} = \sigma 2^{-2H(I)}$
  - distortion decreases by $1/2 = 6\text{dB}$ per bit added
- Consider MDC that interleaves two CE quantizers
  - Receiving both descriptions decreases distortion by factor $1/2 = 6\text{dB}$ compared to single description
  - Small improvement, but FEC has none



Typical Two-Description MDC

- Joint codebook of two descriptions: $\{c_{i_1}^{(1)}, c_{i_2}^{(2)}\}_{i_1 \in I_1, i_{21} \in I_{21}}$
- Central codebook: $\{c_m^{(c)}\}_{m \in M}$,
  - (mappings must exist)
- Mappings: $i_1 = i_1(m), \quad i_2 = i_2(m), \quad m = m(i_1, i_2)$
- Average distortion is:
  - Probability both descriptions arrive: p_c
  - Probability description *1, 2,* nothing arrives: $p_1,\ p_2,\ p_0$

$$d = p_C d(x, c_m^{(c)}) + p_1 d(x, c_{i_1}^{(1)}) + p_2 d(x, c_{i_2}^{(2)}) + p_0 d_0$$

Two-Description MDC: Operation

1. Get data value x

2. Find m that minimizes mean distortion:

$$d = p_C d(x, c_m^{(c)}) + p_1 d(x, c_{i_1(m)}^{(1)}) + p_2 d(x, c_{i_2(m)}^{(2)}) + p_0 d_0$$

3. Transmit

$$i_1 = i_1(m), \quad i_2 = i_2(m)$$

4. Decode:
   1. mapping $m = m(i_1, i_2)$
   2. if both arrive $c_{m(i_1,i_2)}^{(c)}$
   3. if 1 arrives $c_{i_1}^{(1)}$
   4. if 2 arrives $c_{i_2}^{(1)}$

Two Description Index Mappings

- High packet loss solution
  - Allows two similar descriptions

$i_1(m)$ \ $i_2(m)$	0	1	2	3
0	0			
1	1	2		
2		3	4	
3			5	6

m → 3

- No packet loss solution
  - Descriptions very dissimilar

$i_1(m)$ \ $i_2(m)$	0	1	2	3
0	0	1	2	3
1	4	5	6	7
2	8	9	10	11
3	12	13	14	15

Design Problem for Two Descriptions

- Constraints:
  - Constrained resolution
  - Constrained entropy
  - (structure joint codebook; lattice)
  - Mapping

- Minimize distortion (CR), fixed number of cells:

$$D = \mathrm{E}[\min_{m} p_c d(X, c_m^{(c)}) + p_1 d(X, c_{i_1(m)}^{(1)}) + p_2 d(X, c_{i_2(m)}^{(2)})]$$

- Minimize distortion under rate constraint (CE):

$$D = \mathrm{E}[p_c d(X, c_m^{(c)}) + p_1 d(X, c_{i_1(m)}^{(1)}) + p_2 d(X, c_{i_2(m)}^{(2)}) + \lambda_1 H(I_1(X)) + \lambda_2 H(I_2(X))]$$

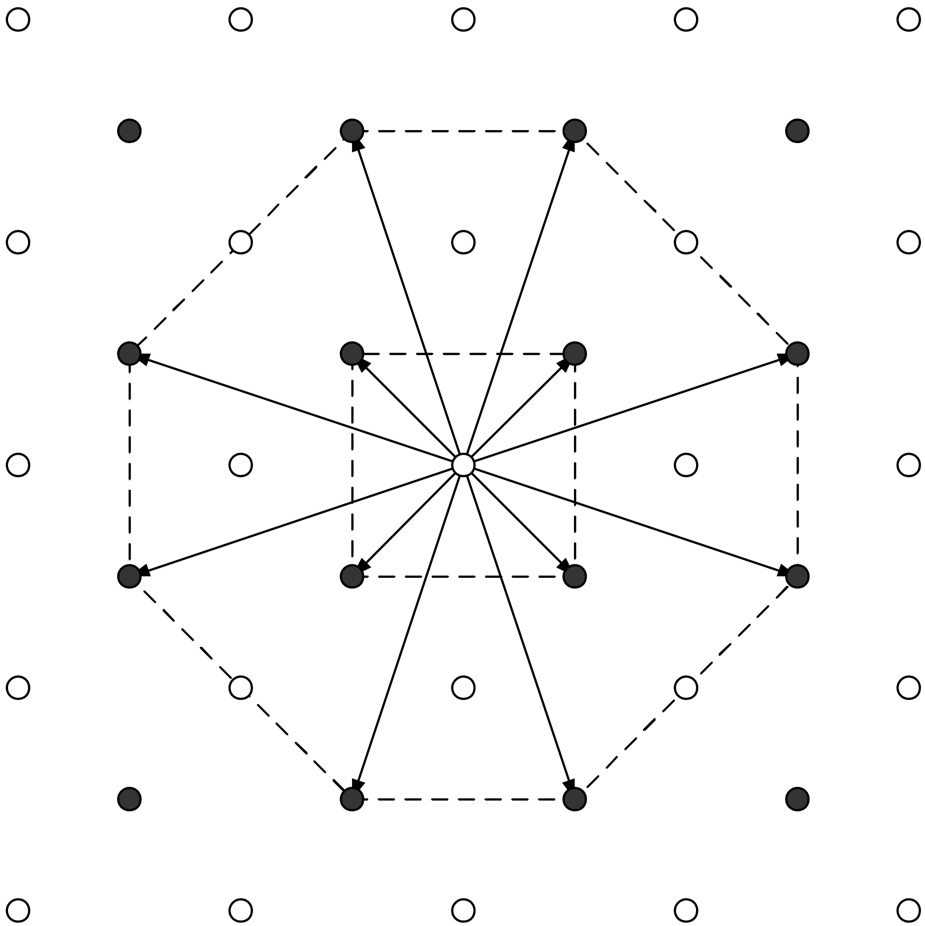
How to Solve Design Problem

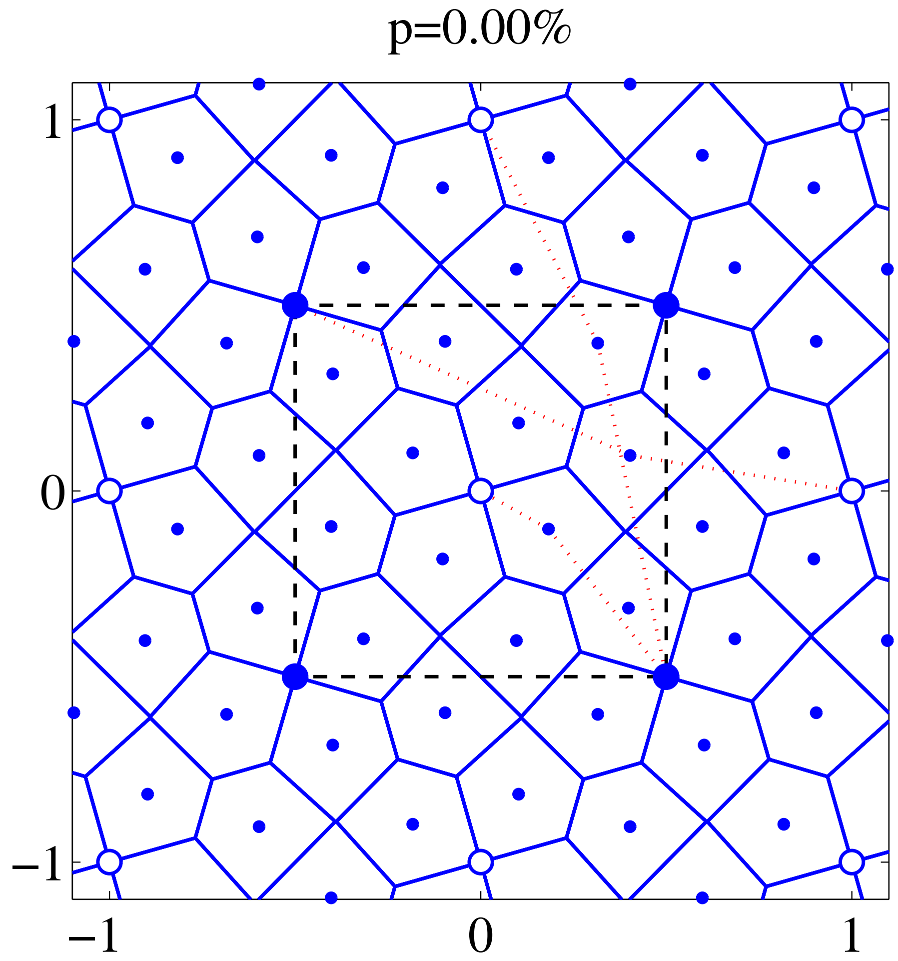
- Generalization of GLA (CR)
  1. Optimize encoder (one)
  2. Optimize decoders (three for two descriptions)
  3. If not converged go to 1

- Generalization of GLA (CE)
  1. Optimize encoder
  2. Optimize decoders
  3. Optimize code lengths
  4. If not converged go to 1

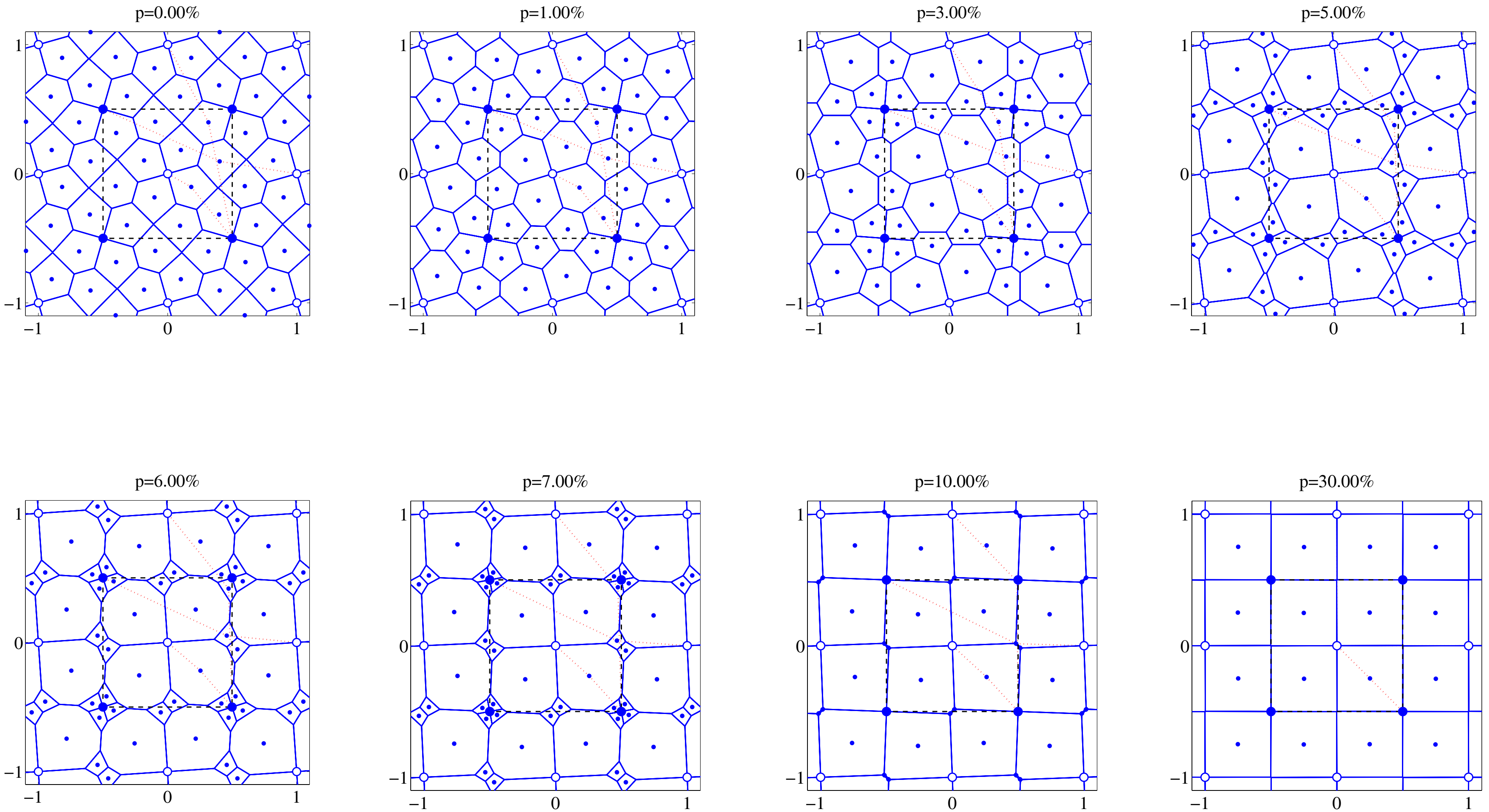
Example Multiple Description Coding

- Zhao/Kleijn 2004





Example Encoder Shifted Lattice MDC

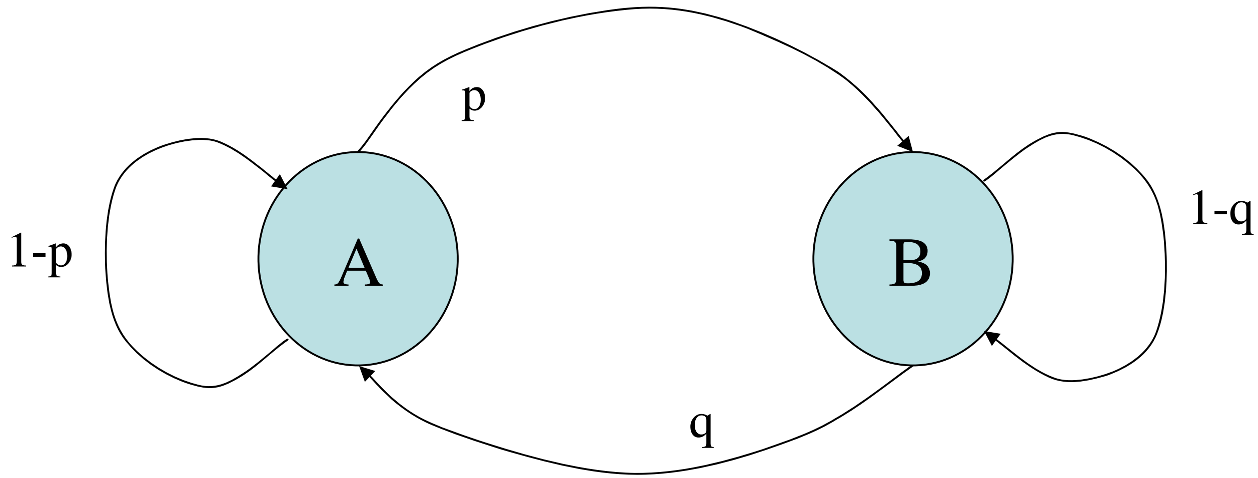


Delays, Packets, and Redundancy

- ITU-T G.114: Voice: <100 ms is toll-quality; 150 ms reasonable limit
- Audio-visual: similar delay requirements
- Packet subject to Maximum Transfer Unit (MTU)
  - Typically 12 kbits
  - Blocks of 10-20 ms easily fit in MTU for audio and video
- Splitting blocks increases overhead
- Delay budget essentially gone with look-ahead, block size, processing, transmission and jitter buffer delays
- No delay available for redundancy; one block is reasonable
- Code two packets simultaneously, double the rate

Practical Comparison

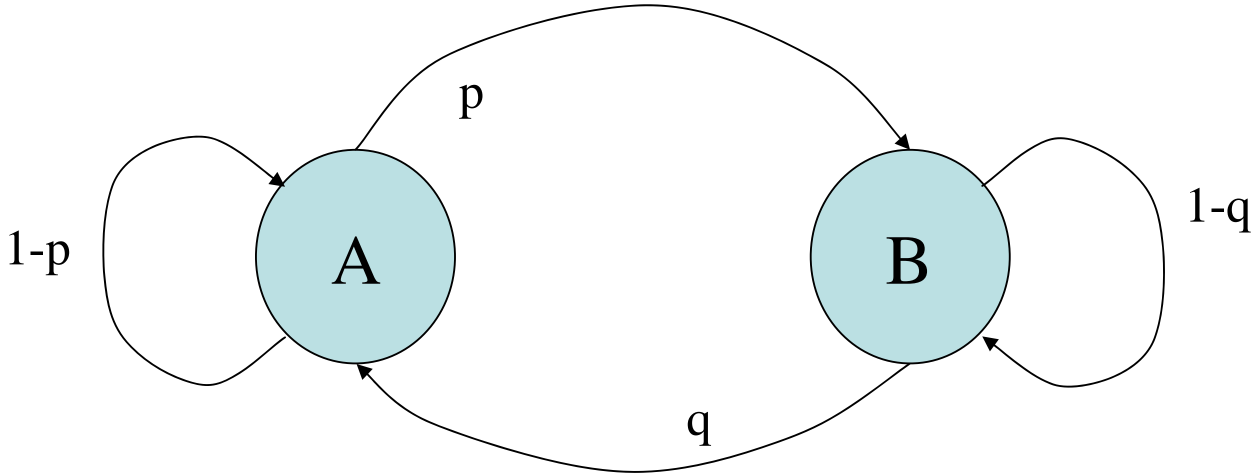
- Two source packets, two redundant packets
  - Delay no more than two packets
- Gaussian source, R-D behavior: $D = 2^{-2H(I)}$
- Gilbert model to simulate packet network



Gilbert Model is Good

- 18000 calls between 9 sites

(dB)	Gilbert	Direct	Gilbert	Direct
Bits/sample	1	1	9	9
FEC	5.81	5.77	26.96	26.68
MDC	7.96	7.88	27.42	26.30
optMDC	10.53	10.47	27.88	26.88



Practical FEC

- Distortion for FEC (Reed-Solomon):
  - At least 2 out of 4 arrive
  - 1 source packet arrives
  - None of the above

$$D_{\mathrm{FEC}} = p_{\mathrm{FEC}} 2^{-2R} + p_{\mathrm{os}}(1 + 2^{-2R}) + p_{\mathrm{nd}} = v_1 2^{-2R} + v_2$$

$$v_1 = \frac{q}{p+q}(2 + 3p - 3p^2 - pq^2 + 3p^2 q)$$

$$v_2 = \frac{q}{2(p+q)}(2 - 3q + 3pq + q^3 - 3pq^2)$$

Practical MDC I

- Distortion for MDC
  - (Interleaved)
  - 2 out of 2 arrive
  - 1 out of 2 arrives
  - None arrive

$$D_{\text{MDC}} = \mathrm{E}[p_c d(X, c_m^{(c)}(X)) + p_1 d(X, c_i^{(1)}(X)) + p_0]$$

- Single channel versus Two channels (better)

Single channel:

$$p_c = \frac{q}{p+q}(1-2p+p^2+pq)$$

$$p_1 = \frac{2pq}{p+q}(2-p-q)$$

$$p_0 = \frac{p}{p+q}(1-2q+q^2+pq)$$

Two channels (better):

$$p_c = \frac{q^2}{(p+q)^2}$$

$$p_1 = \frac{2pq}{(p+q)^2}$$

$$p_0 = \frac{p^2}{(p+q)^2}$$

Bound on Practical MDC II

- Distortion for MDC $D_{\text{MDC}} = \mathrm{E}[p_c d(X, c_m^{(c)}(X)) + p_1 d(X, c_i^{(1)}(X)) + p_0]$

- Rate-distortion bound (out of the blue here; Ozarow):

$$D_C = \begin{cases} \dfrac{2^{-4R}}{1-\left(1-D_1-\sqrt{D_1^2-2^{-4R}}\right)^2}, & 2^{-4R} \le D_1 \le \dfrac{1}{2}(1+2^{-4R}) \\ 2^{-4R}, & D_1 \ge \dfrac{1}{2}(1+2^{-4R}) \end{cases}$$

- Where R is the source rate

Bound on Practical MDC III

- Informed versus non-informed case

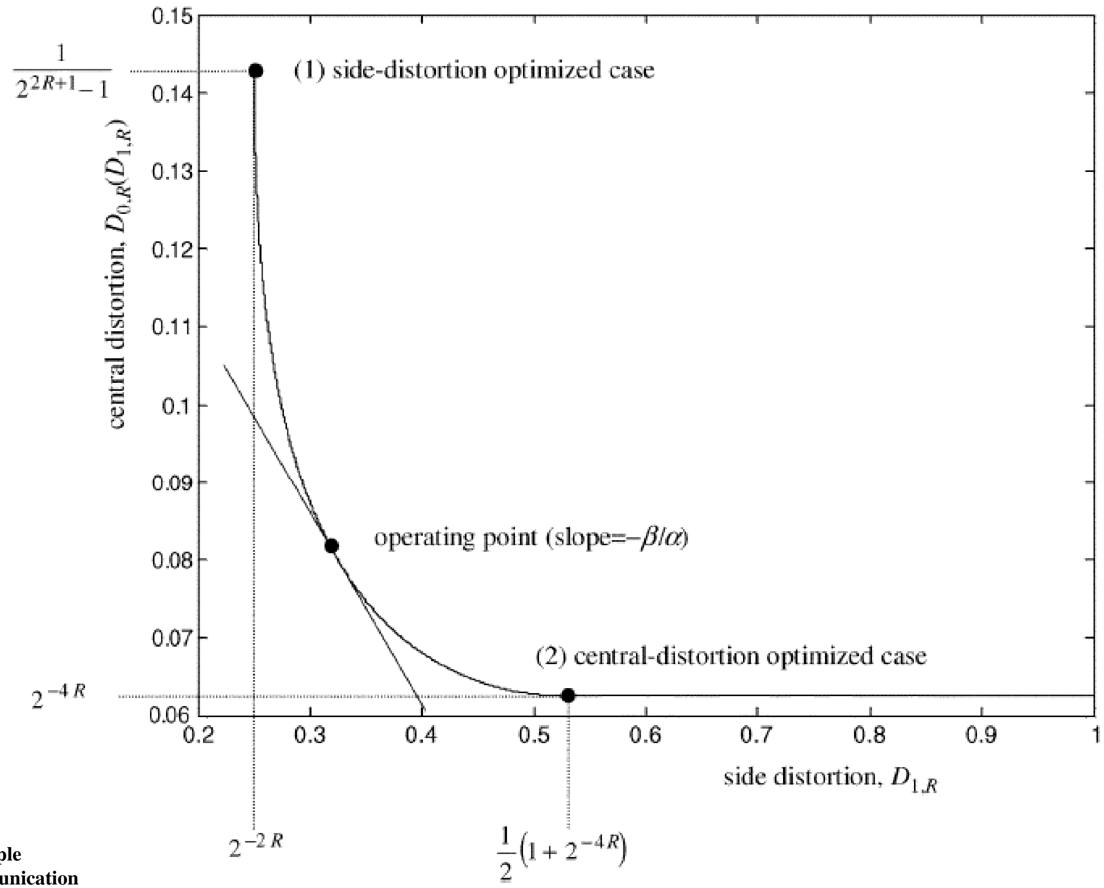


Fig. 3. Achievable R-D bound and operating point of MDC ($R = 1$ b/sample).

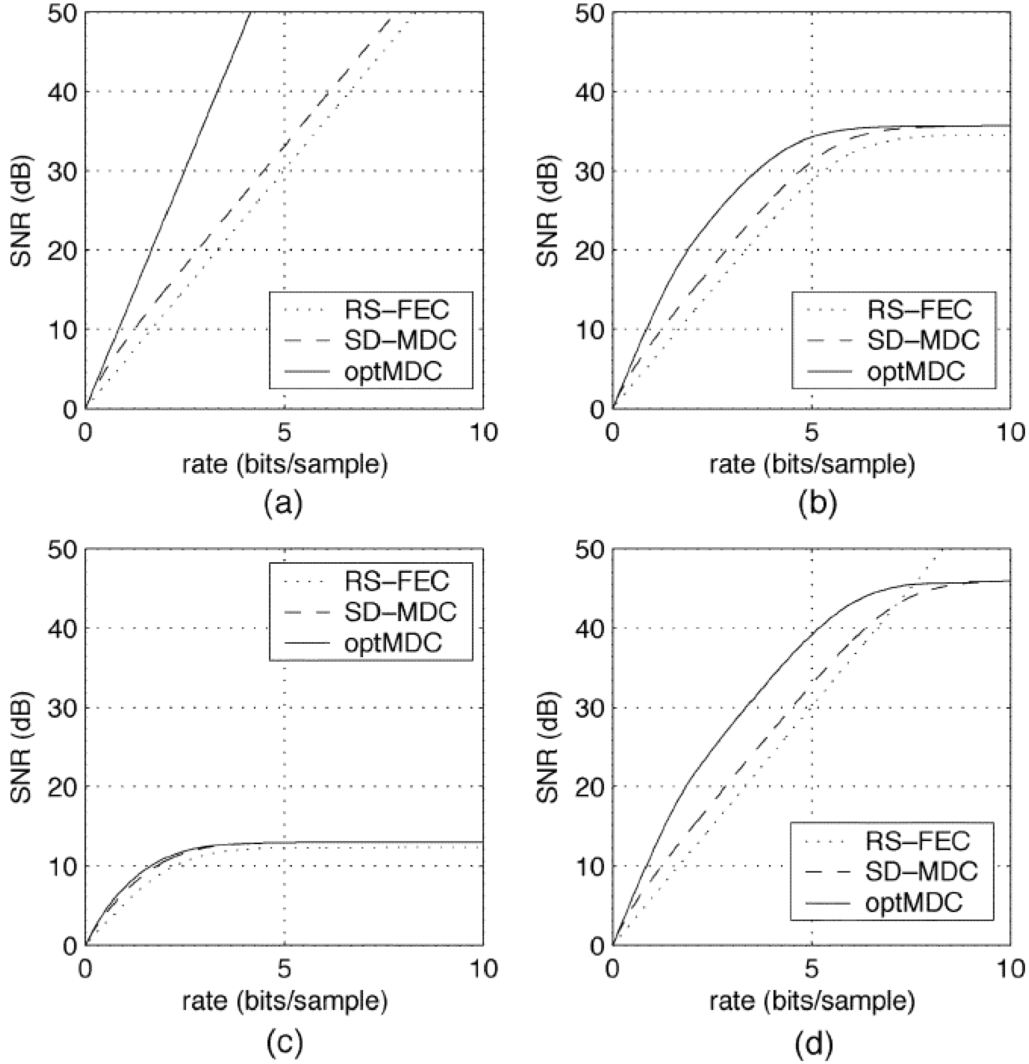
Comparative rate-distortion performance of multiple description coding for real-time audiovisual communication over the Internet
Moo Young Kim; Kleijn, W.B.;
Communications, IEEE Transactions on
Volume 54, Issue 4, April 2006 Page(s):625 - 636

Practical MDC vs FEC

- Single channel case
- Bounded by burst errors

p=0
q=1

p=0.005
q=0.8



p=0.1
q=0.5

p=0.005
q=1

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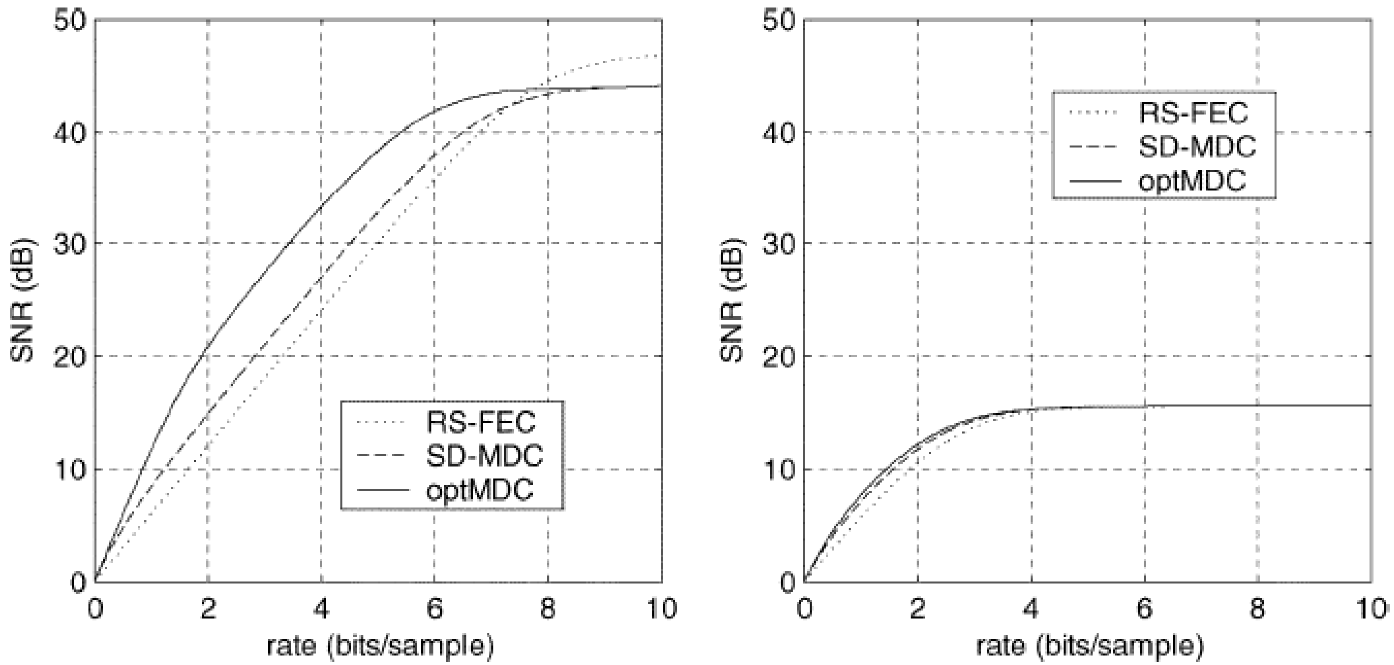
Practical MDC vs FEC

- Two-channel case



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Note on Current Implementations

- Proprietary coders common on Internet
  - Implementation not known
  - MDC likely used
- Usage of legacy coders
  - Addition of FEC layer convenient

Conclusions on MDC and FEC

- MDC minimizes distortion given packet-loss rate
  - MDC failure is inherently graceful
  - Full range of trade-offs
  - Requires new source coders
- FEC prevents info loss up to certain packet loss rate
  - Catastrophic failure
  - Can use legacy coders
  - Redesign difficult
- At high rates: quality constrained by burst errors
  - Consequence of delay constraint