Streaming Source Coding with Delay

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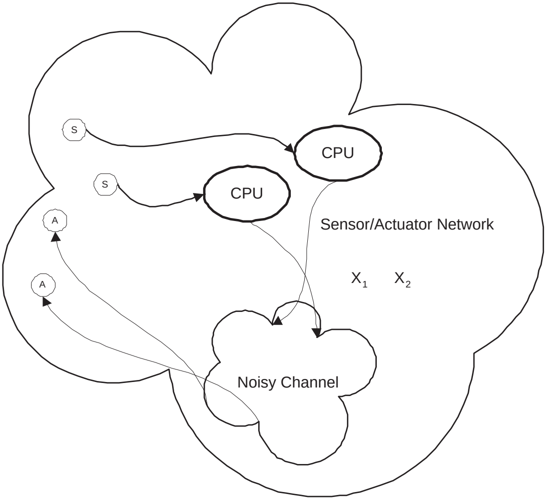
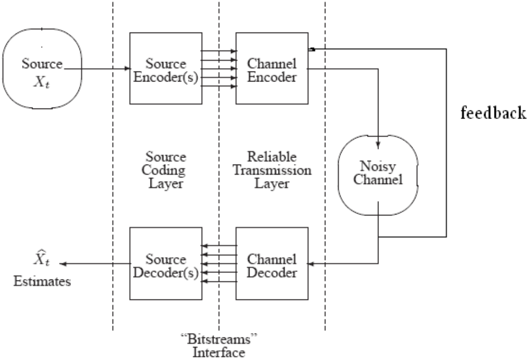
Kannan Ramchandran
David Aldous

Motivation

- Applications which care about end-to-end delay
  - Online gaming, video conferences....
  - Control and Communication (Sahai 2001), Remote surgery...



Source channel coding and delay



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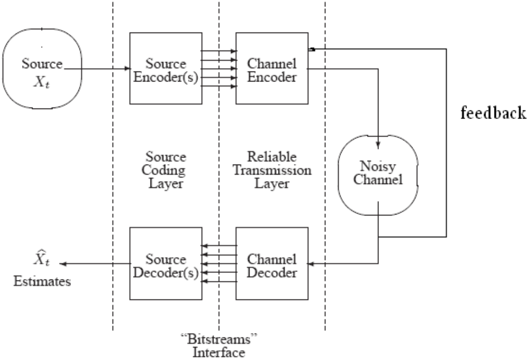

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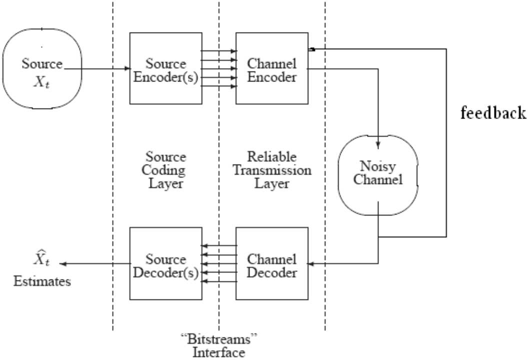

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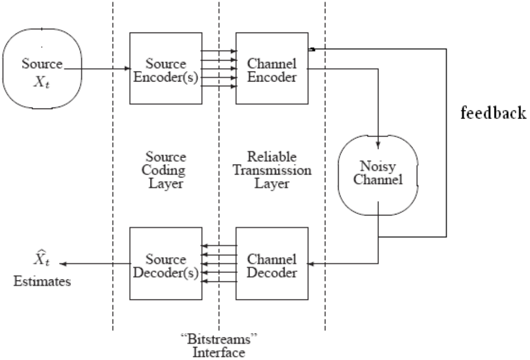
- Hard real-time (Gilbert/ Neuhoff, Shannon), X_t gradually available

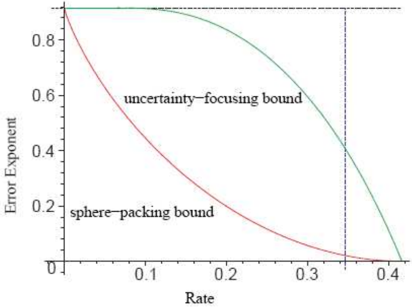
Source channel coding and delay



- Fixed length block coding (Shannon), X_t is a long block ready at time 0
- Hard real-time (Gilbert/ Neuhoff, Shannon), X_t gradually available
- Streaming with long delays (this talk)— X_t gradually available, long delay

Block length and delay are not the same thing (Sahai 2006)

- Streaming feedback error exponent with deterministic delay
  - Upper bound: Focusing bound (Simsek 2004), not completely understood
  - True only if both streaming AND with feedback



What about source coding?

- Streaming source coding with delay (this talk)
  - Complete characterization of the error exponent for point-to-point coding
  - Lower and upper bounds for distributed source coding
  - Price of ignorance

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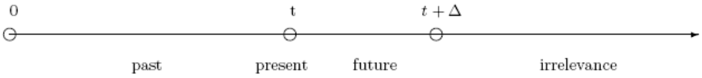
- Streaming source coding with delay (this talk)
  - Complete characterization of the error exponent for point-to-point coding
  - Lower and upper bounds for distributed source coding
  - Price of ignorance
- Why block length and delay are not the same thing?
  - Dominant error event — most likely trouble maker (minimum effort by source/ channel)
  - Block coding: block error events (BSC ($\epsilon = 0.1$) flip half of the bits)
  - Streaming coding, decode X_t at time $t + \Delta$: past vs future (More challenges)



Outline

1. Problem setup and motivation
   - Motivation
   - Streaming coding with delay
2. Main results
   - P2P lossless source coding
   - P2P lossy
   - Distributed source coding
   - Source coding with side-information, an upper bound
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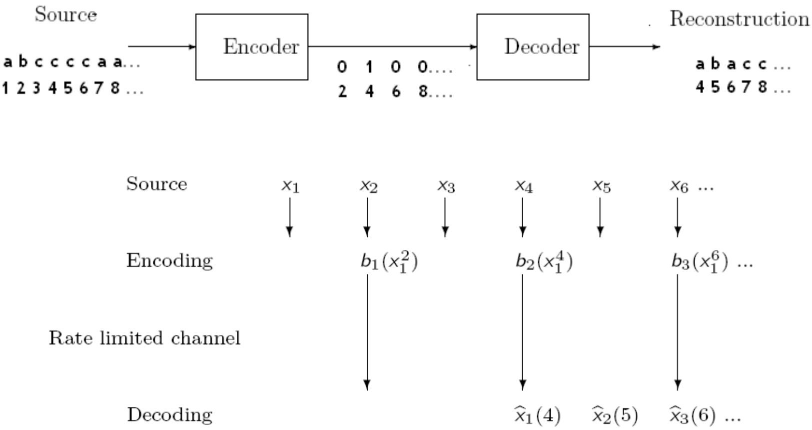
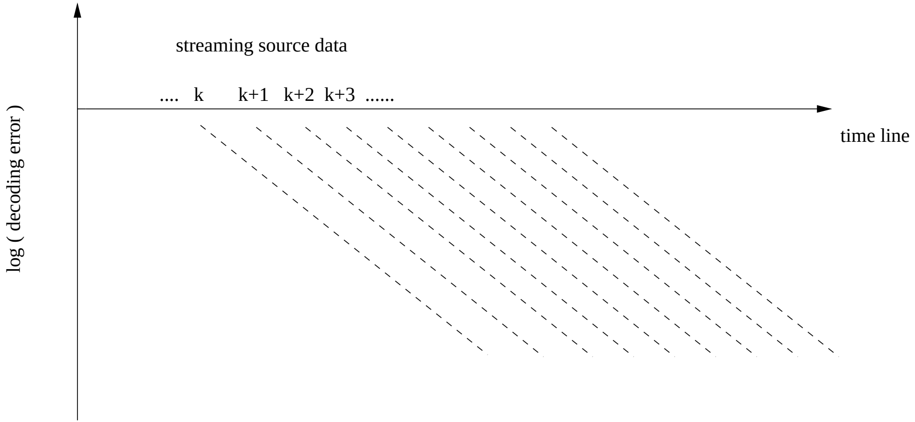
Streaming source coding with delay

- Source $\mathcal{X} = \{a, b, c\}$, $R = \frac{1}{2}$, $\Delta = 3$



Delay constrained error exponent (fixed-delay)

$$\Pr(\widehat{x}_i(i+\Delta) \neq x_i) \sim 2^{-\Delta E(R)} \text{ for large} \Delta$$



Architecture issues: P_e, Δ, R

- Symbol error P_e
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- Communication rate R bits/ second

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- $\Pr(\widehat{x}_i(i+\Delta) \neq x_i) \sim 2^{-\Delta E(R)} \leq P_e$
  - Given P_e and Δ: $R \sim E^{-1}(-\frac{\log P_e}{\Delta})$
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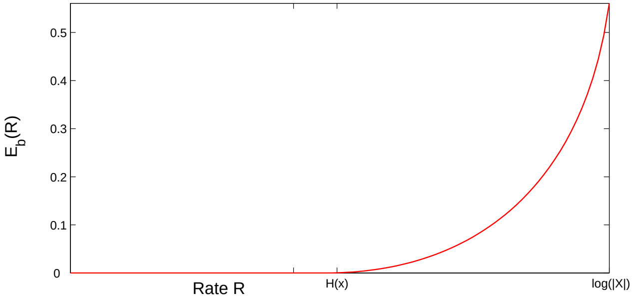
  - Given P_e and R: $\Delta \sim \frac{-\log P_e}{E(R)}$
- Asymptotic result, need non-asymptotic results for small Δ
- Non-asymptotic information theory/ redundancy rate/ Minimum description length/ universal lower bounds on error exponents (Kieffer, Baron, Shamir, Gallager, Sahai, C)

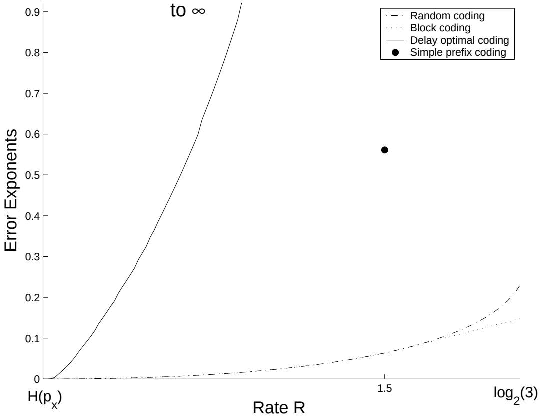
Block coding error exponent (Gallager, Csiszár)

$$E_b(R) = \min_{q:H(q)\geq R} D(q\|p_x) = \sup_{\rho\geq 0}\{\rho R - (1+\rho)\log[\sum_x p_x(x)^{\frac{1}{1+\rho}}]\}$$



The focusing operator

$$E(R) = \inf_{\alpha > 0} \frac{1}{\alpha} E_b((\alpha + 1)R)$$



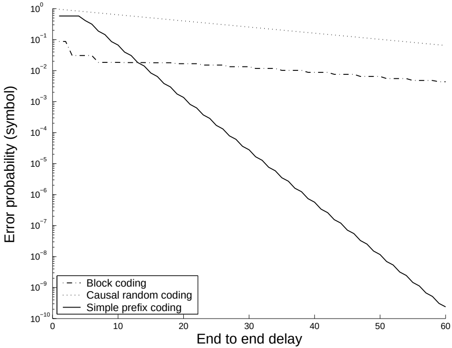
Non-asymptotic result

- A simple variable length code beats block coding (0.65, 0.175, 0.175)

$$AA \longrightarrow 0$$

$$AB \longrightarrow 1000 \;\; AC \longrightarrow 1001 \;\; BA \longrightarrow 1010 \;\; BB \longrightarrow 1011$$

$$BC \longrightarrow 1100 \;\; CA \longrightarrow 1101 \;\; CB \longrightarrow 1110 \;\; CC \longrightarrow 1111$$



Achievability: Variable length code + FIFO queue

- Streaming data to streaming blocks $x_1, x_2, ... \rightarrow x_1^N, x_{N+1}^{2N}, ...,$
  $1 \ll N \ll \Delta <$buffer

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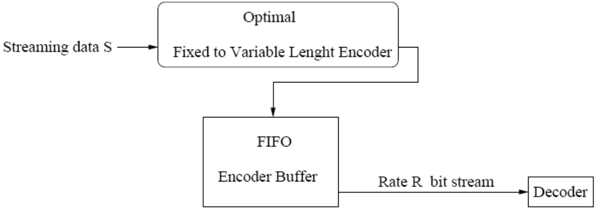

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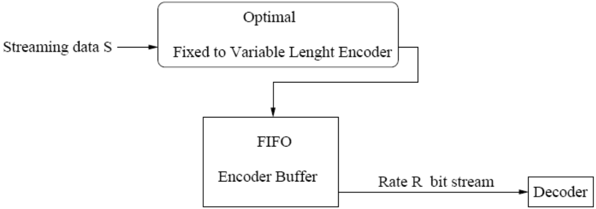
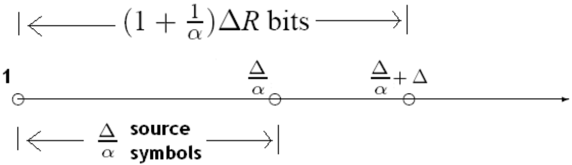


- Decoding error $\rightarrow$ long queueing delay
- Long queueing delay $\Leftrightarrow$ buffer overflow (Jelinek 1968, Merhav 1991)
- Optimal among all coding schemes

Converse: a focusing bound argument

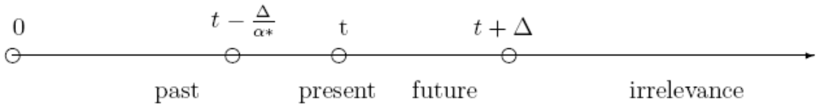
- Use $(1+\frac{1}{\alpha})\Delta R$ bits to describe $x_1, x_2, ...x_{\frac{\Delta}{\alpha}}$, $\frac{\Delta}{\alpha}$ source symbols
- $\alpha = \frac{future}{past}$
  - Streaming coding with delay $\rightarrow$ block coding
  - Block length $\frac{\Delta}{\alpha}$, rate $(1+\alpha)R$



- Delay constrained coding $\rightarrow$ classical fixed length block coding
  - Block error $\sim 2^{-\frac{\Delta}{\alpha}E_b((1+\alpha)R)}$
  - True for all $\alpha > 0$: $E(R) = \inf_{\alpha>0} \frac{1}{\alpha}E_b((\alpha+1)R)$

Dominant error event

- Past, present, future and remote future for decoding x_t at time $t + \Delta$



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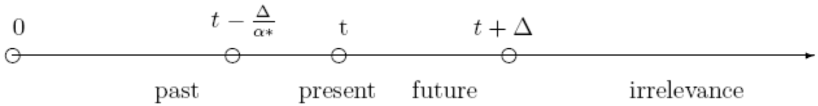

- Source behaves like the ρ^*-tilted distribution of $p_x^{\rho^*}$ from time $t - \frac{t}{\alpha^*}$ to time t

$$p_x^{\rho^*}(x) = \frac{p_x(x)^{\frac{1}{1+\rho^*}}}{\sum_{s \in \mathcal{X}} p_x(s)^{\frac{1}{1+\rho*}}}, \quad \rho^* R = (1+\rho*)\log[\sum_x p_x(x)^{\frac{1}{1+\rho^*}}], \quad \alpha^* + 1 = \frac{H(p_x^{\rho^*})}{R}$$

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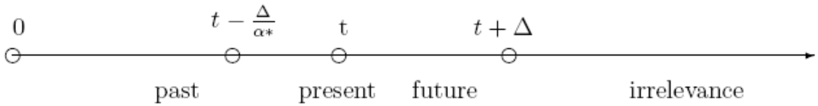

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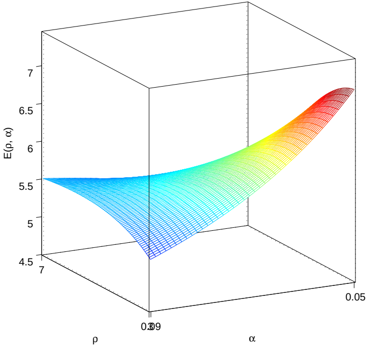
- Parametrization $E(R) = \rho^* R$

A game theoretic perspective on $E(R)$

- (ρ^*, α^*) is the saddle point

$$E(R) = \inf_{\alpha>0} \frac{1}{\alpha} E_b((\alpha+1)R) = \inf_{T>\alpha>0} \sup_{\rho>0} \frac{1}{\alpha}(\rho(1+\alpha)R - (1+\rho)\log[\sum_x p_x(x)^{\frac{1}{1+\rho}}])$$



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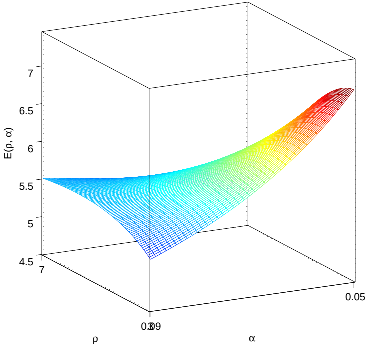
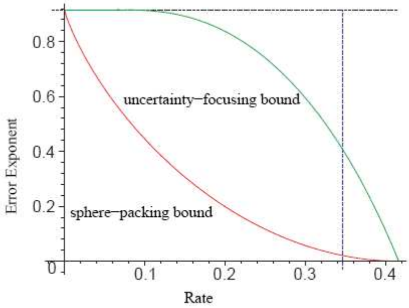
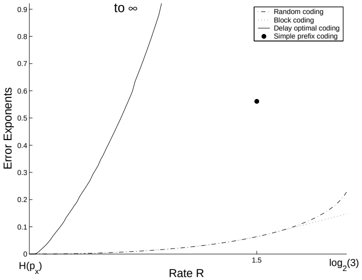


- Payoff is the symbol error, adversary picks α, Jelinek picks ρ-tilted entropy code

Focusing operators

- Channel coding with feedback $\inf_{0 \leq \lambda \leq 1} \frac{E_{sp}(\lambda R)}{1-\lambda}$: (Simsek and Sahai, 2006)
- Source coding: $E(R) = \inf_{\alpha > 0} \frac{1}{\alpha} E_b((\alpha+1)R)$





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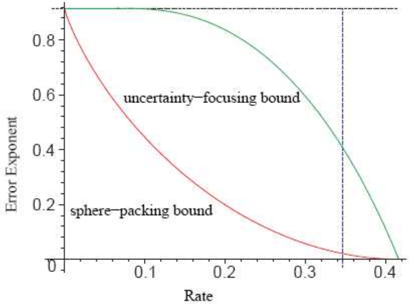
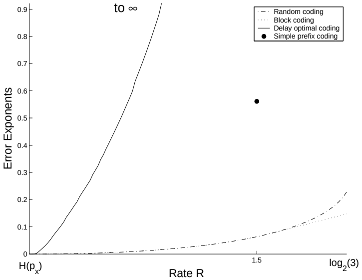
- Duality: $\frac{\Delta}{\alpha}$ symbols using $R(\Delta + \frac{\Delta}{\alpha})$ bits $\leftrightarrow$ $\frac{\lambda}{1-\lambda} \Delta R$ bits using $\frac{\Delta}{1-\lambda}$ channel uses





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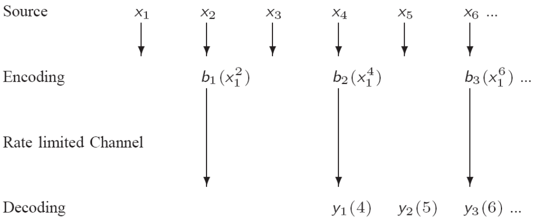

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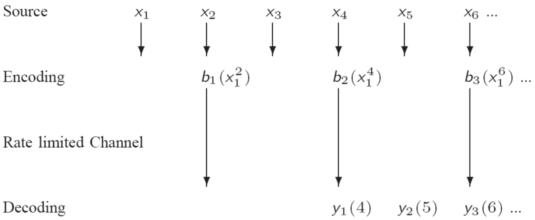

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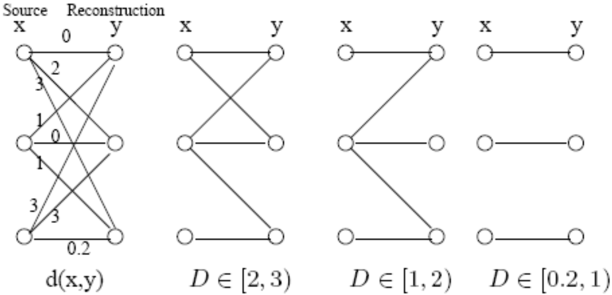
$$\Pr(d(x_i, y_i(i + \Delta)) > D) \sim 2^{-\Delta E_D(R)}$$

- No-delay (Gilbert, Neuhoff 1982), average distortion (Tse 1993)

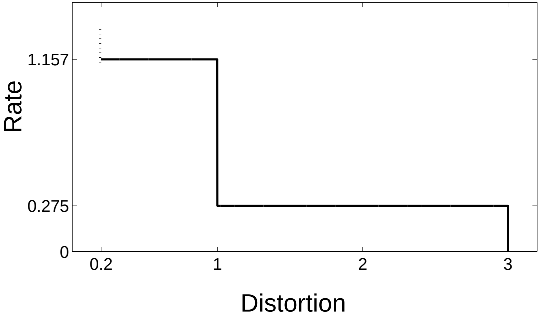
Peak Distortion Measures

- $d(x_1^n, y_1^n) = \max_i d(x_i, y_i)$
- Block coding under peak distortion $\longleftrightarrow$ streaming lossy
- Distance $d(x, y)$ and valid reconstructions



$R(D)$ is a stair function (Csiszár and Körner)

- $R(D)$ not convex on D, $p_x = \{0.2, 0.7, 0.1\}$



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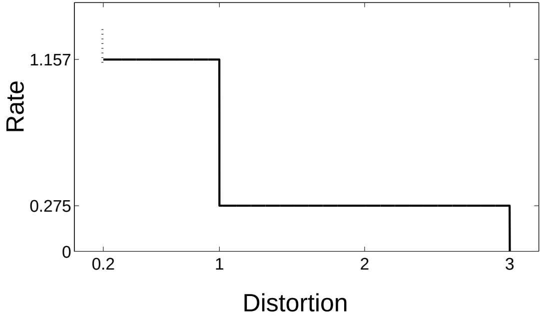

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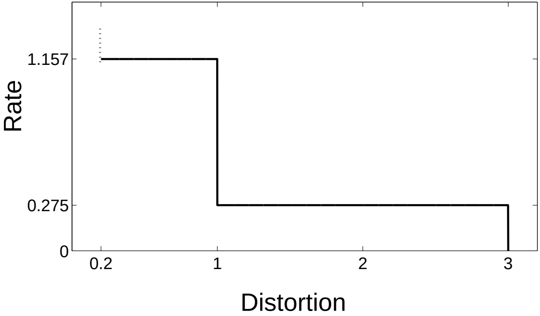
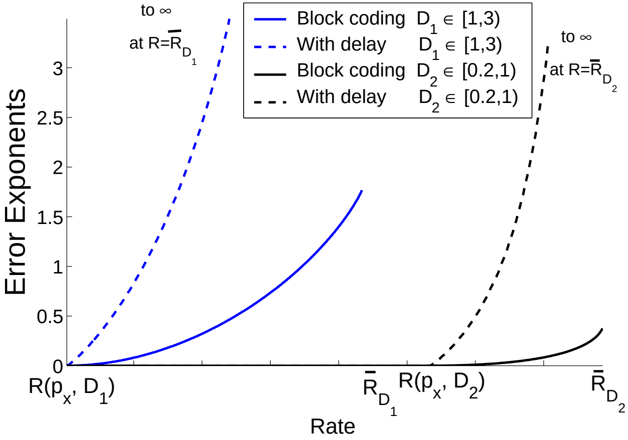


- Block coding error exponent $E_D^b(R)$ (Marton, 1974)
- Scalar quantization is suboptimal (not lossless), $R(p_x, D \in [1,3]) < H(0.9, 0.1) = 0.469$

Lossy source coding error exponent

- $\Pr(d(x_i, y_i(i+\Delta)) > D) \sim 2^{-\Delta E_D(R)}$
  - $E_D(R) = \inf_{\alpha>0} \frac{1}{\alpha} E_D^b((\alpha+1)R)$
  - Cannot be parameterized unlike lossless— general proof



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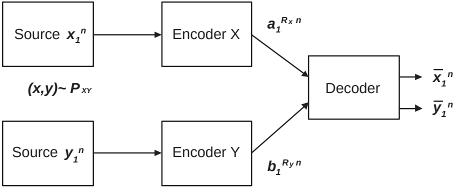
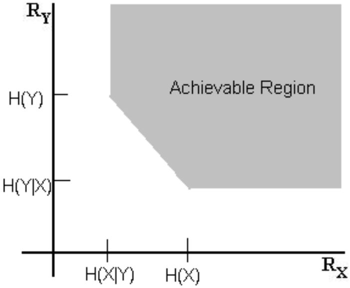
Distributed source coding (C, Draper, Sahai 2006)

- Lossless Source Coding of Correlated Sources

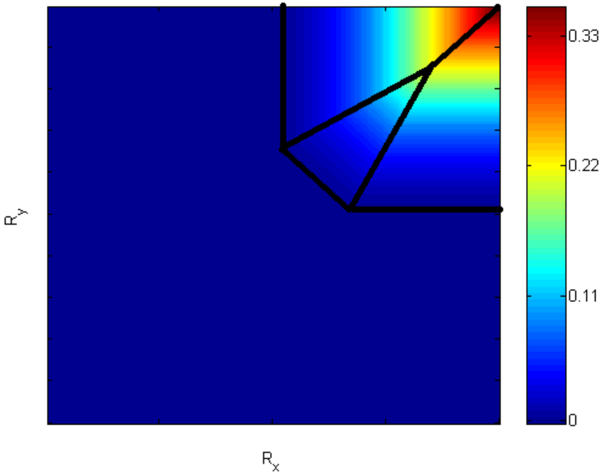


- Rate region (Slepian, Wolf)



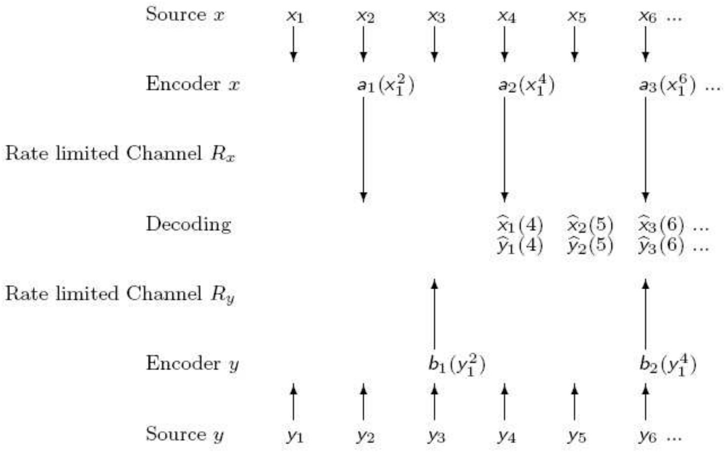
Block coding error exponents: (Gallager, Csiszár)

- $\Pr[(x^n, y^n) \neq (\hat{x}^n, \hat{y}^n)] \sim 2^{-n \min\{E_{xy}, E_{x|y}, E_{y|x}\}}$
- Three dominant error events: xy, $y|x$ and $x|y$



Streaming Slepian-Wolf coding with fixed delay

$(x, y) \sim P_{xy}$, $\Delta = 3$, $R_x = 1/2$, $R_y = 1/3$



Sequential Random Binning

- Block random binning $\Pr(b(x_1^n) = b(\tilde{x}_1^n)) = 2^{-nR}$ if $x_1^n \neq \tilde{x}_1^n$

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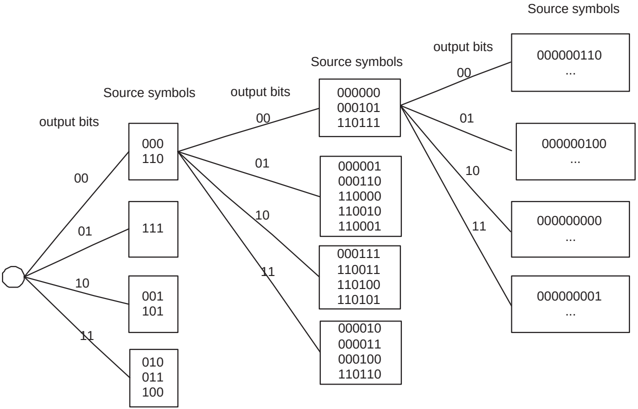
- Sequential Random binning $\Pr(b(x_1^n) = b(\widetilde{x}_1^n)) = 2^{-(n-i)R}$, t is the first position $x_i \neq \widetilde{x}_i$



ML decoding (re-estimate (x_1^n, y_1^n) at time n)

- $(\widehat{x}_1^n, \widehat{y}_1^n) = arg \max_{b_X(s_1^n)=b_X(x_1^n), b_Y(t_1^n)=b_Y(y_1^n)} p_{xy}(s_1^n, t_1^n)$
  - Stack algorithm (Palaiyanur, Sahai)

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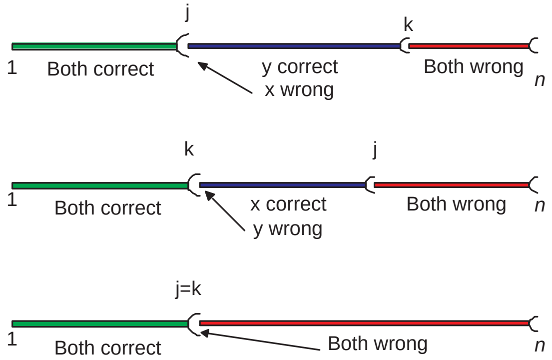
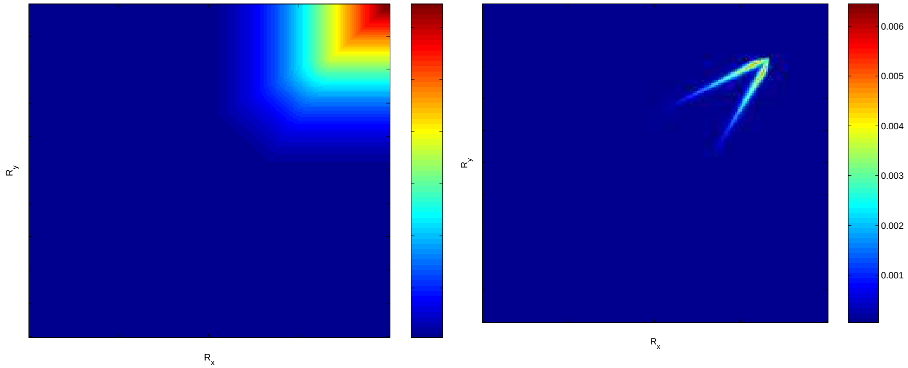
  - Sequential minimum empirical entropy (Draper, C, Sahai)
- Partition of error events at time n (first divergent position):



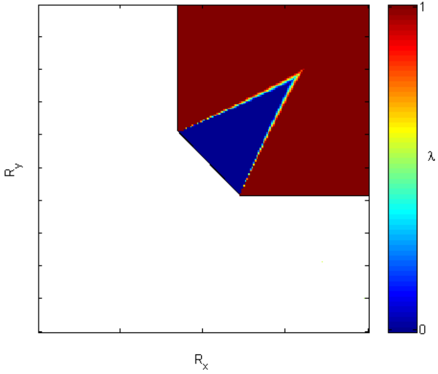
Delay constrained error exponents: $E(R_x, R_y)$ and $E_{block} - E_{delay}$

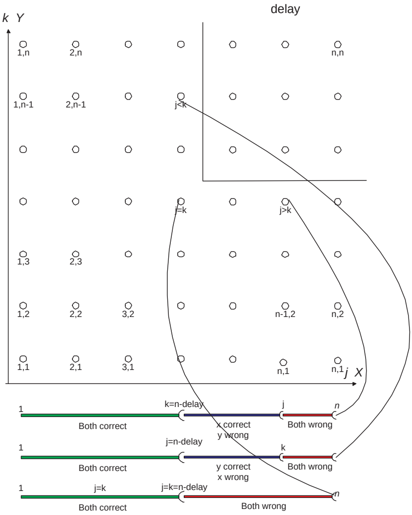
0.1	0.05
0.05	0.8



Dominant error event for streaming coding

- $E(R_x, R_y) = \min\{\inf_{\gamma \in [0,1]} E_x(R_x, R_y, \gamma), \inf_{\gamma \in [0,1]} E_y(R_x, R_y, \gamma)\}$



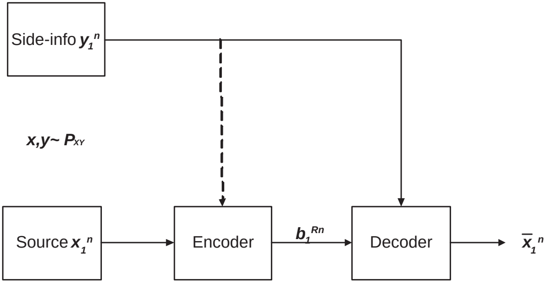


No upper bound?

Outline

Lossless Source Coding with side-information

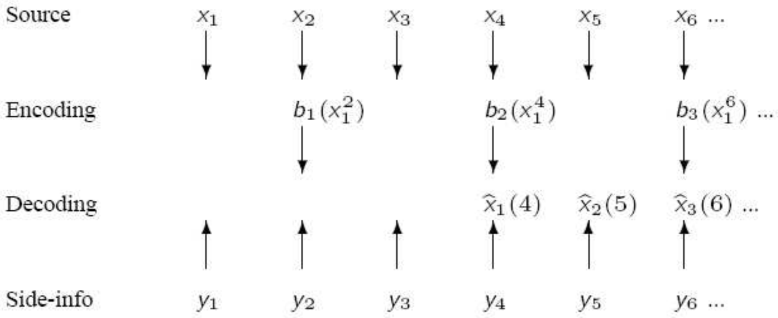
- Special case of Slepian-Wolf (Encoder Y perfect)



  - $R \geq H(X|Y)$ to achieve ϵ-error probability $(x_1^n \neq \bar{x}_1^n)$ - Slepian and Wolf
  - Encoder side-information redundant

Streaming coding with delay

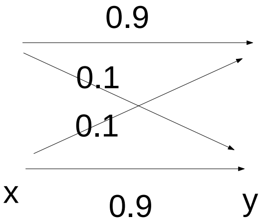
- Streaming source coding with delay constraints



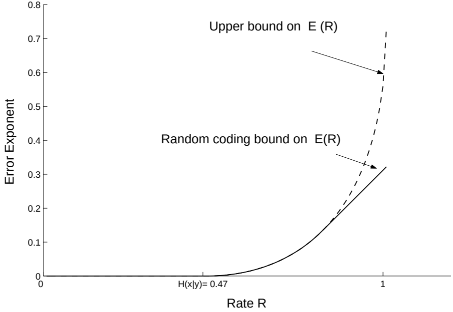
  - Symbol decoding error exponential decays with delay

$$\Pr(x_i \neq \widehat{x}_i(i+\Delta)) \sim 2^{-\Delta E(R)}$$

Example: x uniform and $P_{y|x}$ symmetric channel



- X ~Bernoulli (0.5),
- $A \sim$ Bernoulli (0.1)
- $Y = X \bigoplus A$



- Decoder side-info only: tight in low rate regime!

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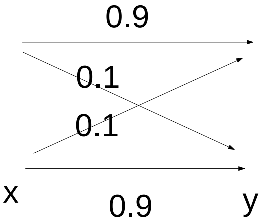

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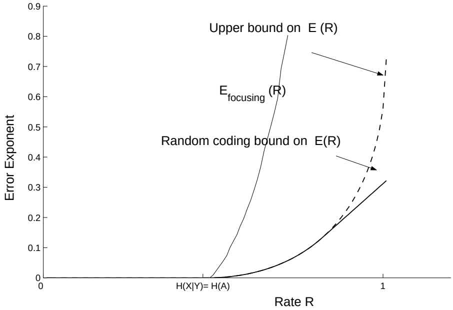

- Decoder side-info only: tight in low rate regime!
- With encoder side-info, focusing bound.
- Price of ignorance.

Compression of Encrypted Data (Johnson et al)

- Compression $\longrightarrow$ Encryption $\longrightarrow$ Decryption $\longrightarrow$ Decompression
  - Delay constrained source coding error exponent $E_{focusing}(R)$

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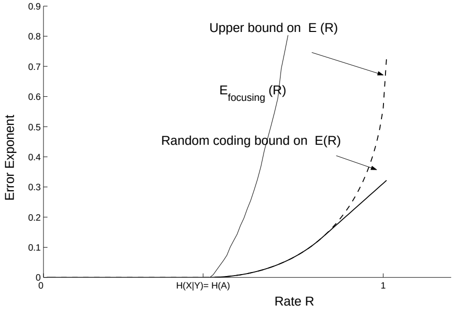
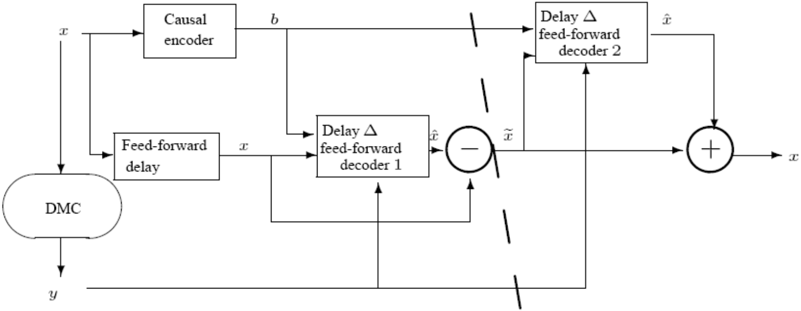


Proof of the upper bound

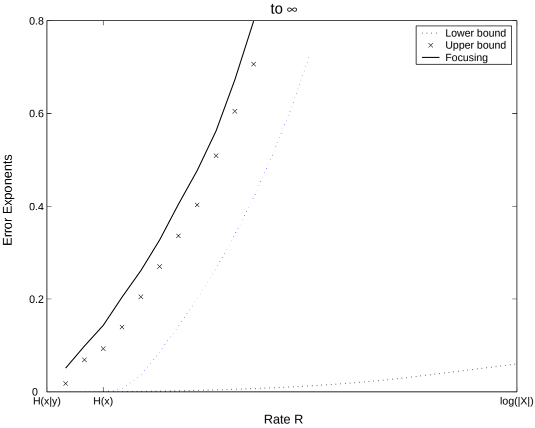
- Feed-forward channel decoding (Pinsker, Sahai)
  - Joint source-channel coding

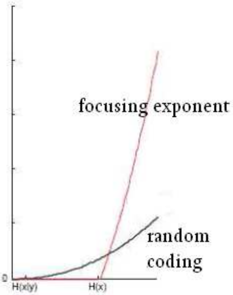


- Computational complexity/ rate tradeoff for iterative decoding (Grover, Sahai)
  - Delay $\longleftrightarrow$ neighbors on the graph (resource)

Bounds on $E(R)$

- Lower bounds:
  - Sequential random binning — $R > H(X|Y)$
  - Variable length coding + FIFO — $R > H(X)$



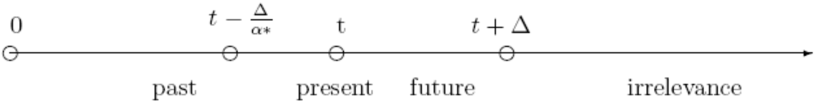


Outline

1. Problem setup and motivation
   - Motivation
   - Streaming coding with delay
2. Main results
   - P2P lossless source coding
   - P2P lossy
   - Distributed source coding
   - Source coding with side-information, an upper bound
3. Conclusions and future works
   - Past vs future
   - Open problems

Dominant error events for optimal coding

- Streaming source coding, channel coding with delay



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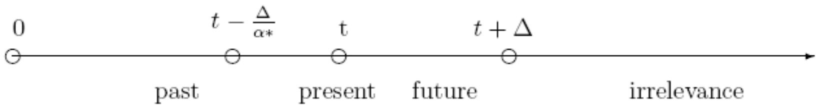

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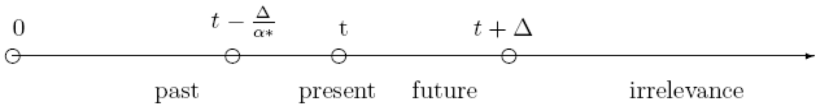

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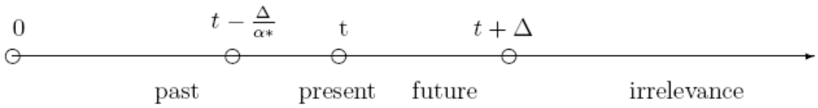

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Interaction between encoder and decoder

- Focusing operator
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- From the encoder's perspective:
  - Variable length code/ Queue $\longrightarrow$ observable randomness (source)
  - Sequential random binning $\longrightarrow$ non-observable randomness (channel, decoder side-information)
  - Variable length sequential random binning? (Joint source-channel, decoder side information)

Other future directions

- Binary representation of streaming coding with delay problems (p-to-p)

	Random arrival	Non-uniform source	Noisy DMC channel	Feedback	Side-information	Distortion
lossless	0	1	0	0	0	0
lossy	0	0	0	0	0	1
decoder side-info	0	0	0	0	1	0
ongoing work	1	1	0	0	0	0
Joint SC	0	1	1	0	0	0
Pinsker, Sahai	0	0	1	0	0	0
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- With memory?
- Universal lower bound on the error exponents— non asymptotic result.
- Convexity $\bigcup$ of the focusing bound $E(R)$?