Distortion-Optimal Transmission of Progressive Images over Channels with Random Bit Errors and Packet Erasures

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Homayoun Yousefi'zadeh
Hamid Jafarkhani
Farzad Etemadi

Department of EECS, UCI
[hyousefi, hamidj, fetemadi]@uci.edu

Problem Description

- Transmit a packetized progressive bitstream such as SPIHT or JPEG2000 over a noisy channel such that

  (1) Distortion-Optimal Problem: The distortion of reconstructed image is minimized, or

  (2) Rate-Optimal Problem: The number of useful source coding bits is maximized.

Literature Review

- **Source Coding**

  [Shapiro] Embedded zerotrees of wavelets

  [Said et al.] Set Partitioning in Hierarchical Trees (SPIHT)

  [Taubman et al.] Progressive wavelet-based subband image coding

  [Ordentlich et al.] Embedded coding of the bitplanes of a wavelet-transformed image

  [Malavar] Another progressive wavelet coding technique

- **Hybrid Schemes**

  [Srinivas et al.] Utilizing a maximum a posteriori (MAP) detector to compensate for the impacts of spatially correlated compressed bitstream and interleaving for temporally correlated channel errors

  [Cosman et al.] Without investigating optimality showed the potential advantage of adding channel coding to wavelet-based zerotree encoded images and reordering the resulting bitstream into packets with a small set of wavelet coefficient trees

- **Channel Coding and JSCC**

  [Sherwood et al.] Concatenated a source coder bitstream with an outer CRC coder and an inner rate compatible punctured convolutional (RCPC) coder

  [Chande et al.] Dynamic programming (DP) for solving rate-optimal problem over BSC; exhaustive search for channels with memory

  [Banister et al.] Exhaustive search for solving a distortion-optimal JPEG2000 coded problem over BSC with outer CRC and an inner punctured turbo coders, Sub-optimal problem solved using DP

  [Stankovic et al.] Accelerated optimal strategy of [Chande at al.] in BSC case

  [Appadwedula et al.] Utilized exponential estimates of D-R curve to analytically solve the distortion-optimal problem over BSC

  [Lu et al.] Solved a distortion-optimal problem relying on data fitting techniques over BSC. Conservative estimates of the error probability of channels with memory

Contributions

- Addressing the following voids:
  - Provide a systematic study of the subject material for the noisy channels with temporally correlated random bit errors and packet erasures, and
  - Consider the effects of communication system components including modulation, channel coding, and multiple antennas.

Statistical Optimization Framework

- In each round, split the available bandwidth between the two components

  (1) random bit errors: utilize distortion- or rate-optimal approach,

  (2) packet erasures: statistically guarantee the delivery of a block of PKTs.
- Utilize rate-compatible punctured RS codes
- Use feedback for retransmitting lost information in multiple rounds.
- Framework is applicable to both fixed- and variable-size packets for as long as there is no segmentation/reassembly of UDP or ATM packets over Ethernet and/or IEEE 802.11 frames.

Parameter Settings

- Bandwidth split factor between the two components: $0 < a < 1$
- Fixed packet size: L
- BS_A represents the accumulated transmitted bitstream in each round and never exceeds BS_R.
- B_T represents total available budget.
- Number of packets:

$$N = \min\left(\left\lfloor a\frac{B_T}{L}\right\rfloor, \left\lfloor \frac{BS_R - BS_A}{L}\right\rfloor\right)$$

- Feedback Format

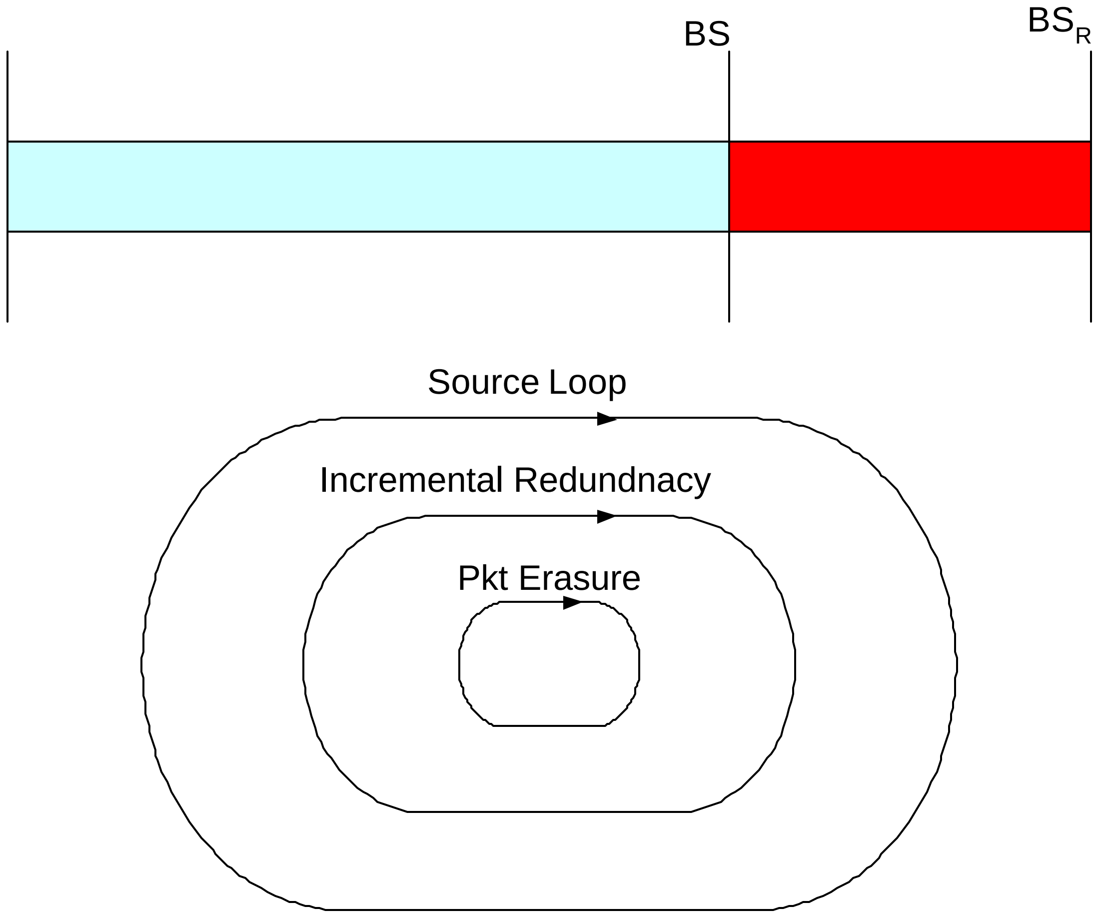
  2 bits per pkt bitmap

  R: (MSB,LSB)=(0,x)

  FB: (MSB,LSB)=(1,0)

  FE: (MSB,LSB)=(1,1)

End-to-End Protocol Logic



BS

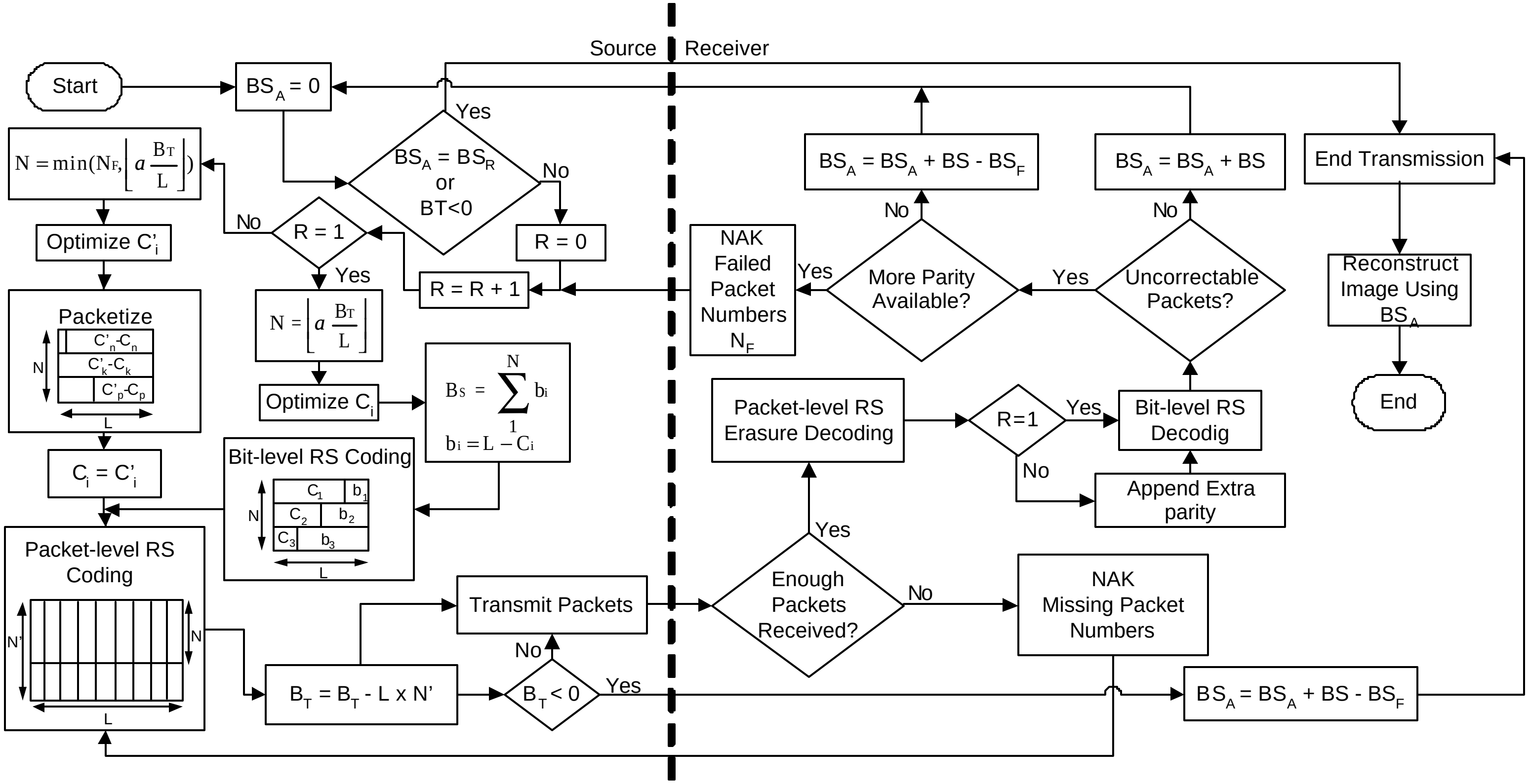
BS_R

Source Loop

Incremental Redundnacy

Pkt Erasure

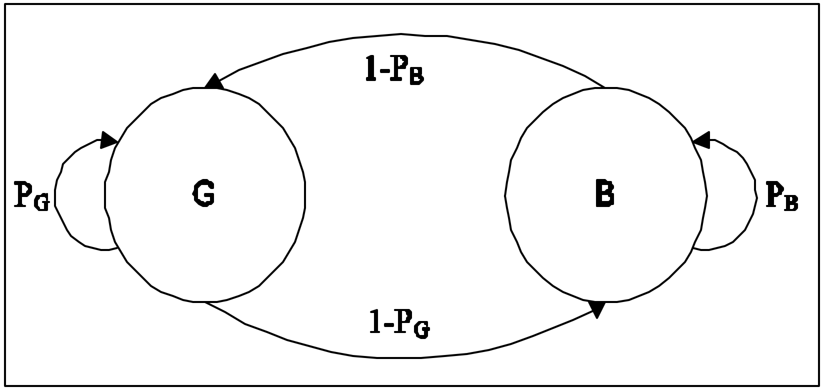
End-to-End Protocol Type II hybrid FEC+ARQ



Channel Description

- Loss is correlated and described by the 2-State Gilbert/Gilbert-Elliott MC
- State transition probs are measured from avg burst length $P_G = g\,,\ \ P_B = b$
- Gilbert Model:

  A UOI (bit/pkt) is received/lost if the system is in State G/B



- Gilbert-Elliott Model:

  Loss Probabilities are Non-Trivial $e_G \ll e_B$

Reception Probabilities

- What is the prob. of receiving exactly k UOIs from n transmitted UOIs?

$$P(n,k)=P(n,k,G)+P(n,k,B), \quad n \geq k > 0$$

$$\begin{aligned} P(n,k,G) &= e_G\,[g\,P(n-1,k,G)+(1-b)P(n-1,k,B)] \\ &\quad +(1-e_G)[g\,P(n-1,k-1,G)+(1-b)P(n-1,k-1,B)] \end{aligned}$$

$$\begin{aligned} P(n,k,B) &= e_B\,[(1-g)\,P(n-1,k,G)+b\,P(n-1,k,B)] \\ &\quad +(1-e_B)[(1-g)\,P(n-1,k-1,G)+b\,P(n-1,k-1,B)] \end{aligned}$$

$$P(0,0,G)=g_{ss}=\frac{1-b}{2-g-b}, \quad P(0,0,B)=b_{ss}=\frac{1-g}{2-g-b},$$

$$P(1,0,G)=e_G\,[g\,g_{ss}+(1-b)\,b_{ss}], \quad P(1,0,B)=e_B\,[(1-g)\,g_{ss}+b\,b_{ss}]$$

Modulation and Coding

- Rate-Compatible Punctured RS Codes
  - Random Bit Errors: G-E Channel
  - Packet Erasures: Gilbert Channel
- SER of SISO w/ BPSK $e_{G,B} = 0.5\ (1 - \sqrt{SNR_{G,B}/(1+SNR_{G,B})})$

  SER of MIMO (2x2) w/ BPSK

$$e_{G,B} = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{SNR_{G,B}}{2+SNR_{G,B}}}\left(\sum_{\mathrm{j}=0}^{3}\binom{2\mathrm{j}}{\mathrm{j}}\frac{1}{[2(2+\mathrm{SNR}_{\mathrm{G,B}})]^{j}}\right)$$

- Probability of Block Loss

$$t_c = \left\lfloor \frac{n-k}{2} \right\rfloor \qquad \Psi(n, t_c, e_G, e_B, g, b) = 1 - \sum_{i=n-t_c}^{n} P(n,i)$$

Random Bit Errors

- Distortion-Optimal Problem
  Solved with SQP+Line Search
  Estimated D-R curve $D_i(b_i)=\sum_{j=1}^{4} h_j e^{-l_j b_i}$

- Round 1 $\min_{C_1,\ldots,C_N}$ $E[D]=D_0\Psi_1+\sum_{i=2}^{N+1}\Psi_i D_{i-1}\prod_{j=1}^{i-1}(1-\Psi_j)$

$$\text{Subject To}: \sum_{i=1}^{N} R_i = \sum_{i=1}^{N}(L-C_i) \le BS_R - BS_A$$

$$0 \le R_i, C_i < L,\ R_i + C_i = L,\ i \in\ 1,\ldots,\mathrm{N}$$

Notes: $b_i=\sum_{j=1}^{i} R_j$ $D_0=\sum_{j=1}^{4} h_j$ $\Psi_{N+1}\overset{\triangle}{=}1$

- Rounds 1+
  Set $\Psi_i=0,\ i\in R$

$$\sum_{i\in F}(C'_i - C_i) \le NL;$$

$$C'_i = C_i,\ \ i\in R;$$

$$C_i \le C'_i \le L_{max} - (L - C_i),\ \ i\in F$$

Packet Erasures

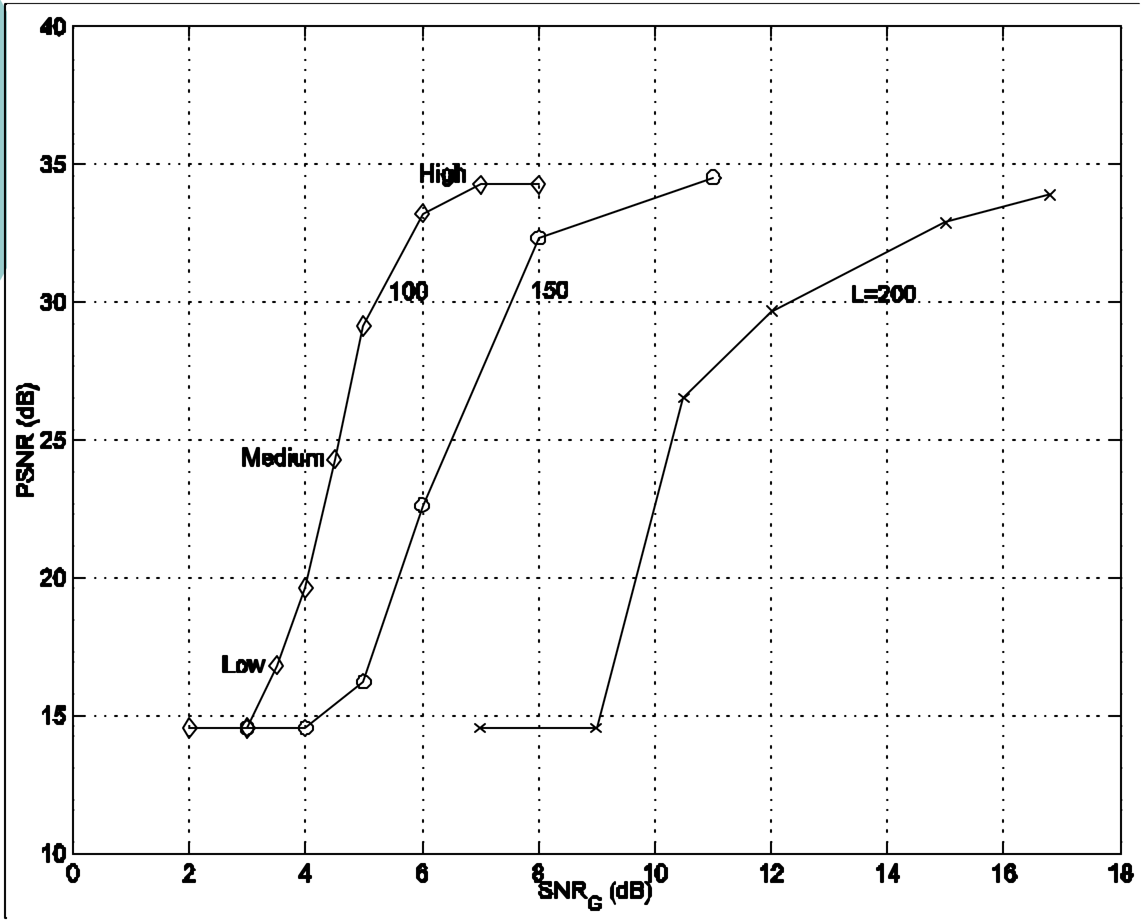
Statistically Guarantee the Arrival of Minimum k PKTs from $n=k+z$ transmitted PKTs with probability Π or better.

- **Initialize** $D(k,k)=g^{k}\frac{1-b}{2-g-b}+g^{k-1}(1-b)\frac{1-g}{2-g-b}$
- $for \quad (z=1 \quad to \quad k) \quad \{$
    - **Calculate** $D(k+z,k)=D(k+z-1,k)+P(k+z,k,G)+P(k+z,k,B)$
    - **If** $D(k+z,k)\geq\Pi$ **Break**

  $\} \quad /* \; for \quad (z=1 \quad to \quad k) */$
- **Report the number of required packets,** $n=k+z$

Complexity $O(z\,k),\ z\ll k$ vs. recursive complexity $O(k^2)$

Plots of $PSNR = 10\log_{10}\frac{255^2}{E[D]}$ vs SNR_G



- SPIHT encoded 512x512x8 bpp gray scale Lena image
- Avg. Burst Length: 8

  $g = 0.99873$ and $b = 0.875$
- $BS_R = B_T = 512 \times 512$
- RS codes with a maximum length 256 over GF(256)
- $SNR_G = 10 SNR_B$
- $a = 0.2$ and $\Pi = 0.95$

Sample Lena Images (L=100Bytes)

Clockwise top-left:

- Original image,
- Reconstructed image at
  - SNR_G=3.5dB,
  - SNR_G=4.5dB,
  - SNR_G=7dB

Conclusion

- Summary:
  - A statistical optimization framework for progressive transmission of images over noisy channels with memory
  - Utilized rate compatible punctured RS codes to compensate for random bit errors as well as packet erasures
  - Relying on receiver feedback, integrated bit error and packet erasure results in the form of a type II hybrid FEC-ARQ protocol
- Future work:
  - Optimal bandwidth allocation between the two components of the framework
  - Investigation of one-to-many transmission scenarios

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