CASE I

Joint Source Coding and Transmission Power Management for Energy Efficient Wireless Video Communications

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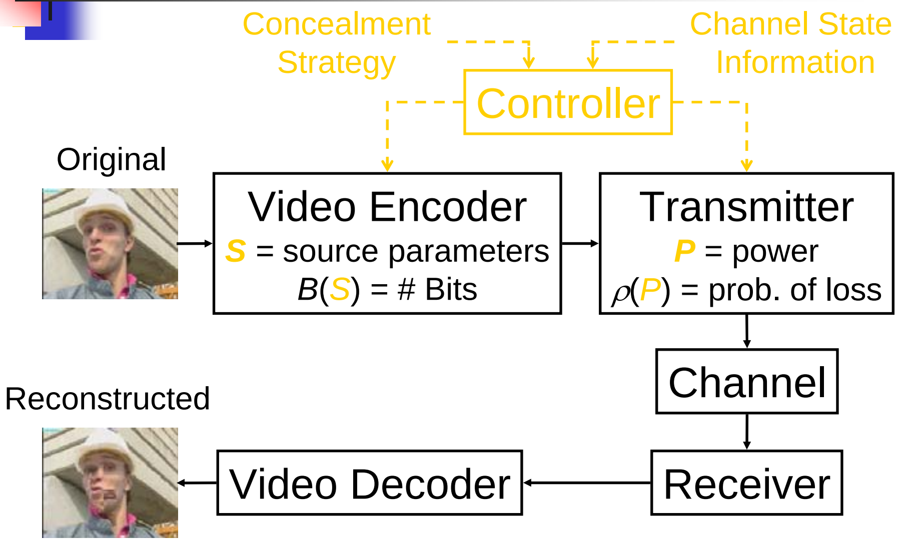
System Model



Concealment Strategy

Channel State Information

Controller

Original

Video Encoder

S = source parameters

$B(S)$ = # Bits

Transmitter

P = power

$\rho(P)$ = prob. of loss

Channel

Reconstructed

Video Decoder

Receiver

Optimization Framework

- Minimum Distortion Approach: Minimize the end-to-end distortion while limiting the transmission energy and delay.

$$\underset{\{S,P\}}{\text{minimize}} \quad D_{tot}(S,P) \qquad \text{End-to-End Distortion}$$

$$\text{subject to:} \quad T_{tot}(S) \leq T_{\max} \qquad \text{Transmission Delay Constraint}$$

$$\mathrm{E}_{tot}(S,P) \leq \mathrm{E}_{\max} \qquad \text{Transmission Energy Constraint}$$

- Dual Formulation: Minimum Energy Approach

Optimization Restated

- **Goal**: Minimize the expected end-to-end distortion while limiting the transmission energy and delay.

$$\underset{\{S,P\}}{\text{minimize}} \quad D_{tot}(S,P) = \frac{1}{K}\sum_{k=1}^{K} E[D_k]$$

$$\text{subject to:} \quad T_{tot}(S) = \sum_{k=1}^{K} \frac{B_k(S_k)}{R} \leq T_{\max}$$

$$\mathrm{E}_{tot}(S,P) = \sum_{k=1}^{K} \frac{B_k(S_k)}{R} P_k \leq \mathrm{E}_{\max}$$

Proposed Algorithm

- Lagrange Relaxation

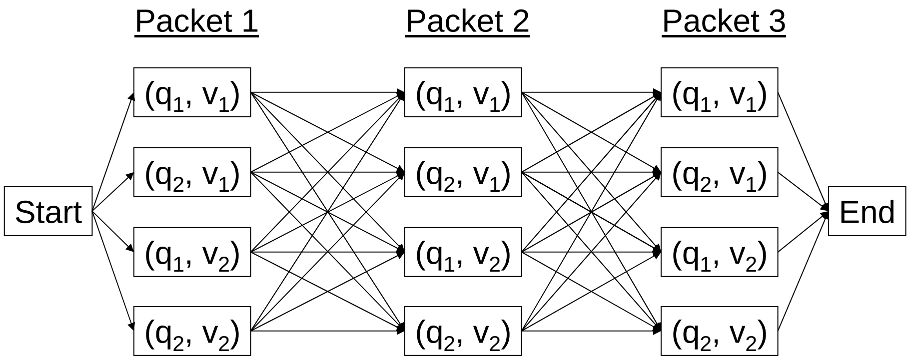
$$\min_{\{S,P\}} J_{tot} = D_{tot}(S,P) + \lambda_1 T_{tot}(S) + \lambda_2 \mathrm{E}_{tot}(S,P)$$

- Dynamic Programming
- Generalized Skip Option

Dynamic Programming

Packet dependencies due to error concealment

(S, P) where $S \in \{q_1, q_2\}$ and $P \in \{v_1, v_2\}$

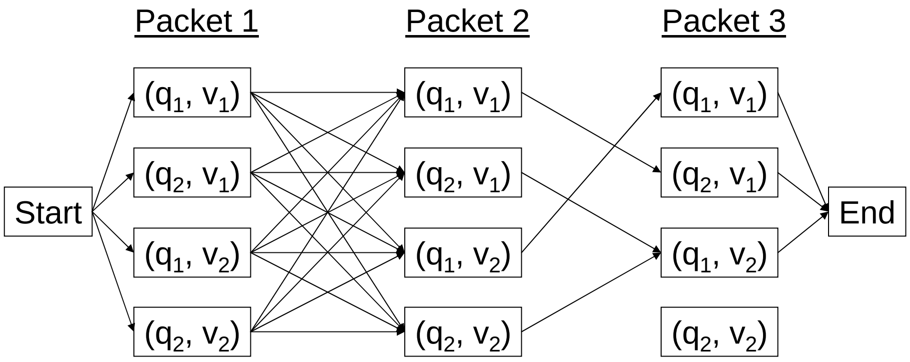


Number of Comparisons Reduced from 64 to 36

Dynamic Programming

- Packet dependencies due to error concealment

(S, P) where $S \in \{q_1, q_2\}$ and $P \in \{v_1, v_2\}$



Packet 1

Packet 2

Packet 3

Start

(q_1, v_1)

(q_2, v_1)

(q_1, v_2)

(q_2, v_2)

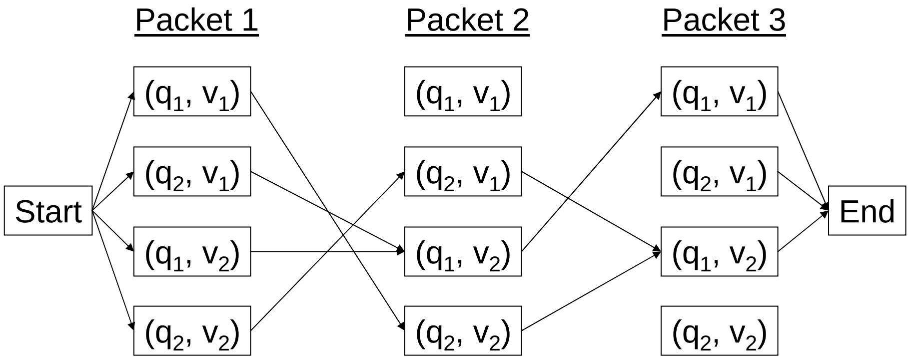
End

Number of Comparisons Reduced from 64 to 36

Dynamic Programming

- Packet dependencies due to error concealment

(S, P) where $S \in \{q_1, q_2\}$ and $P \in \{v_1, v_2\}$



Packet 1

Packet 2

Packet 3

Start

(q_1, v_1)

(q_2, v_1)

(q_1, v_2)

(q_2, v_2)

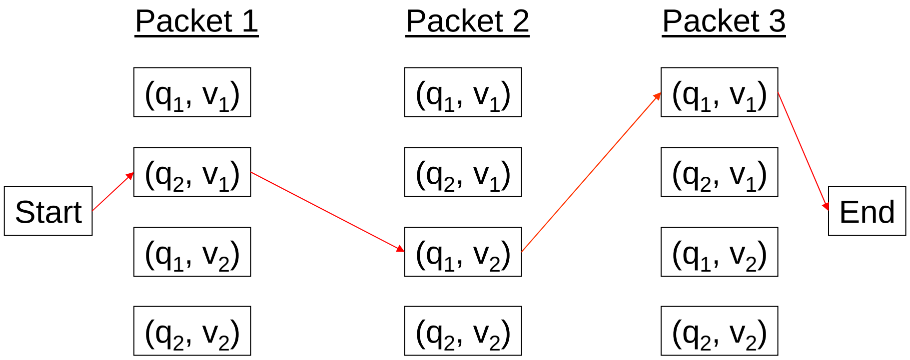
End

Number of Comparisons Reduced from 64 to 36

Dynamic Programming

Packet dependencies due to error concealment

(*S*, *P*) where $S \in \{q_1, q_2\}$ and $P \in \{v_1, v_2\}$



Packet 1

(q_1, v_1)

(q_2, v_1)

(q_1, v_2)

(q_2, v_2)

Packet 2

(q_1, v_1)

(q_2, v_1)

(q_1, v_2)

(q_2, v_2)

Packet 3

(q_1, v_1)

(q_2, v_1)

(q_1, v_2)

(q_2, v_2)

Start

End

Number of Comparisons Reduced from 64 to 36

Proposed Algorithm

- Lagrange Relaxation

$$\min_{\{S,P\}} J_{tot} = D_{tot}(S,P) + \lambda_1 T_{tot}(S) + \lambda_2 \mathrm{E}_{tot}(S,P)$$

- Dynamic Programming
- Generalized Skip Option
  - Don’t transmit when you don’t have to!

Minimum Energy Approach

- Goal: Use the minimum energy to achieve an acceptable level of quality and delay.

$$\underset{\{\mu^k, P^k\}}{\text{minimize}} \qquad \mathrm{E}_{\text{tot}} = \sum_{k=1}^{K} \frac{B^k(\mu^k)}{R} P^k$$

Total Transmission Energy for frame

$$s.t.:$$

$$E\left[D^k\right] = \begin{cases} D_0^k & \forall k: E\left[D_R^k(\mu^k)\right] \le D_0^k \le E\left[D_L^k\right] \\ E\left[D_L^k\right] & \forall k: D_0^k > E\left[D_L^k\right] \end{cases}$$

Maximum Expected Distortion Constraint per packet

and

$$T_{tot} = \sum_{k=1}^{K} \frac{B^k(\mu^k)}{R} \le T_0$$

Delay Constraint for frame

Y. Eisenberg, et al, **"Joint Source Coding and Transmission Power Management for Energy Efficient Wireless Video Communications,"** *Special Issue on Wireless Video, in IEEE Transactions Circuits and Systems for Video Technology*, vol. 12, issue 6, 411-424, June 2002.

Power vs. Probability of Loss

Transmission power for the kth packet

Probability of loss for the kth packet

$$P^k = g\left(\rho^k\right)$$

- Empirical measurements or analytical models can be used by the transmitter to obtain the function $g(\bullet)$
- Example: (outage probability)
  - Narrowband slowly fading channel with AWGN and i.i.d channel fading per packet (L. Ozarow et al, *VT* '94)

$$P^k = g\left(\rho^k\right) = \frac{-C}{\ln(1-\rho^k)} \quad \text{where} \quad C = \frac{N_0 W}{E[H]}\left(2^{R/W} - 1\right)$$

R = channel rate; $E[H]$ = expected channel fade; $N_0 W$ = noise power; W = bandwidth

Min Energy Solution

- Coupling Power to Source Coding Parameters
  - For the distortion constraint
  - Assumption: spatially causal concealment strategy

$$\underset{\{\mu^k\}}{\text{minimize}} \qquad J_{tot} = \sum_{k=1}^{K} J^k(\mu^k)$$

$$J^k(\mu^k) = \begin{cases} \overbrace{\dfrac{B^k(\mu^k)}{R} g\left(\dfrac{E\left[D_L^k\right] - D_0^k}{E\left[D_L^k\right] - E\left[D_R^k(\mu^k)\right]} \right)}^{\text{Energy}} + \lambda \overbrace{\dfrac{B^k(\mu^k)}{R}}^{\text{Delay}} & \text{if } E\left[D_R^k\right] \le D_0^k \le E\left[D_L^k\right] \\ 0 & \text{if } D_0^k > E\left[D_L^k\right] \end{cases}$$

Generalized Skip

Fixed Power Approach

- Power Allocation
  - Packet priority unknown to transmitter
  - Same power per packet
- Source Coding

$$\underset{\{S\}}{\text{minimize}} \qquad D_{tot}(S) = \frac{1}{K} \sum_{k=1}^{K} E[D_k]$$

$$\text{subject to:} \quad T_{tot}(S) = \sum_{k=1}^{K} \frac{B_k(S_k)}{R} \le T_{\max}$$

Experimental Results

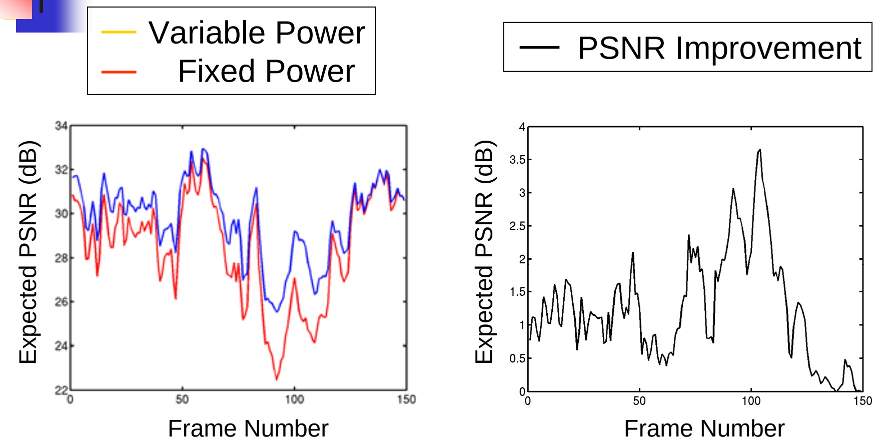
Compare:

- Variable Power Approach
  - Joint Source Coding and Power Allocation
  - min $E[D(S,P)]$; s.t.: $B_{tot}(S) \le B_{max}$, $E_{tot}(S,P) \le E_{max}$
- Fixed Power Approach
  - Independent Source Coding and Power Allocation
  - min $E[D(S)]$; s.t.: $B_{tot}(S) \le B_{max}$

Setup:

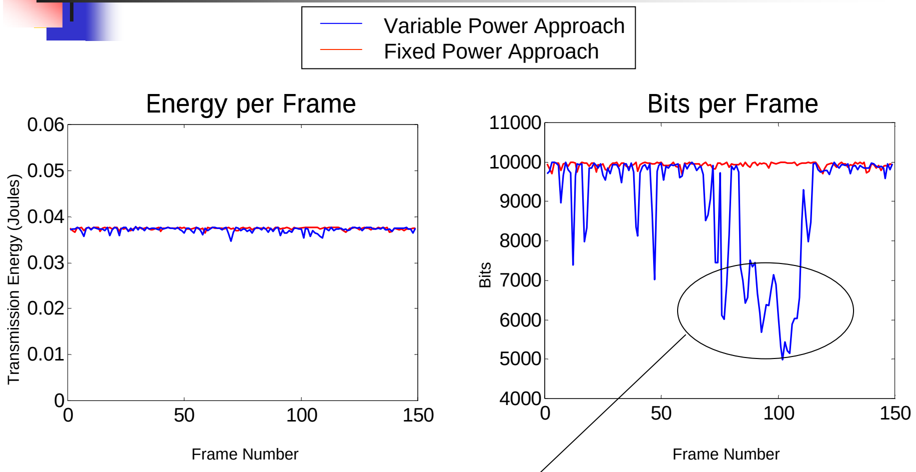
- Fixed Delay Constraint (T_{max} = 33 ms)
- Fixed Transmission Rate (R = 300 kbps)
- Packetization: One MB per packet
- Concealment: Based on Neighboring MB to the left

Expected Distortion Per Frame



“**Foreman**” Sequence: transmission rate = 300 kbps ; avg. prob. of error = 0.20

Energy and Bits per Frame



Better protected bits

Visual Comparison: Slow Motion

Fixed Power Approach

Variable Power Approach

- Same energy and delay constraints per frame
- Approaches differ in source coding and power allocation

Visual Comparison: Real-Time

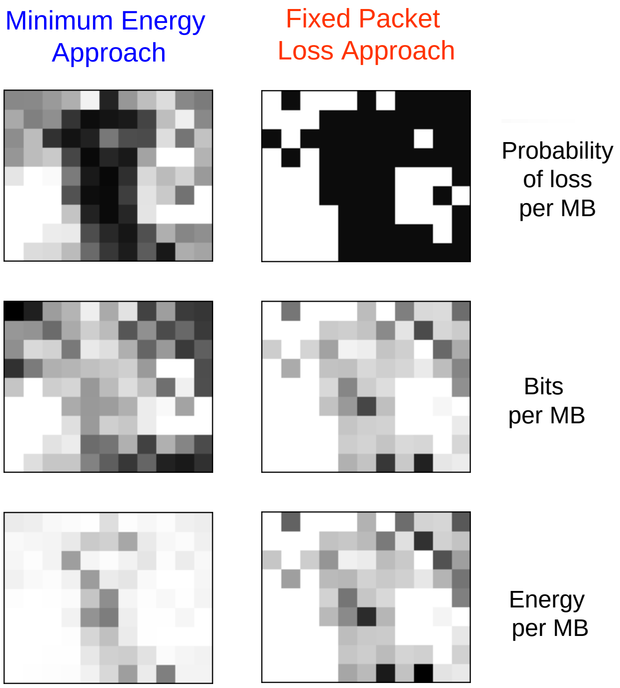
Fixed Power Approach

Variable Power Approach

- How do spatio-temporal artifacts affect the *perceived* video quality?

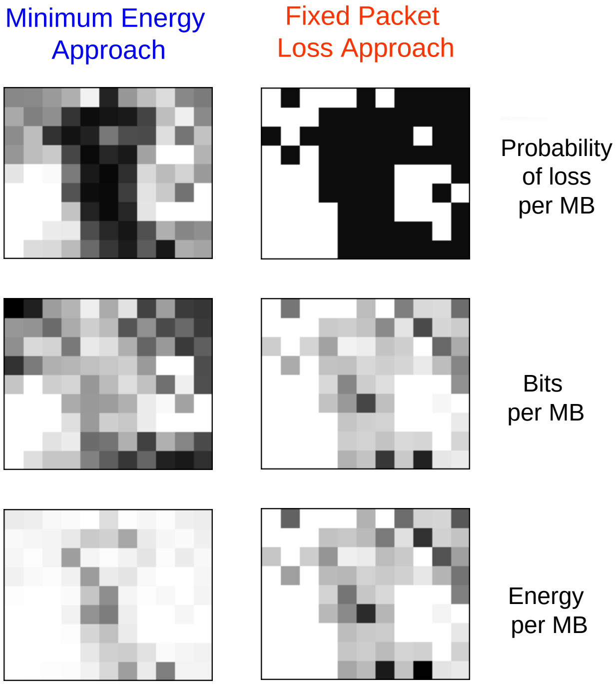
Resource Allocation for Frame 42

Frame 41

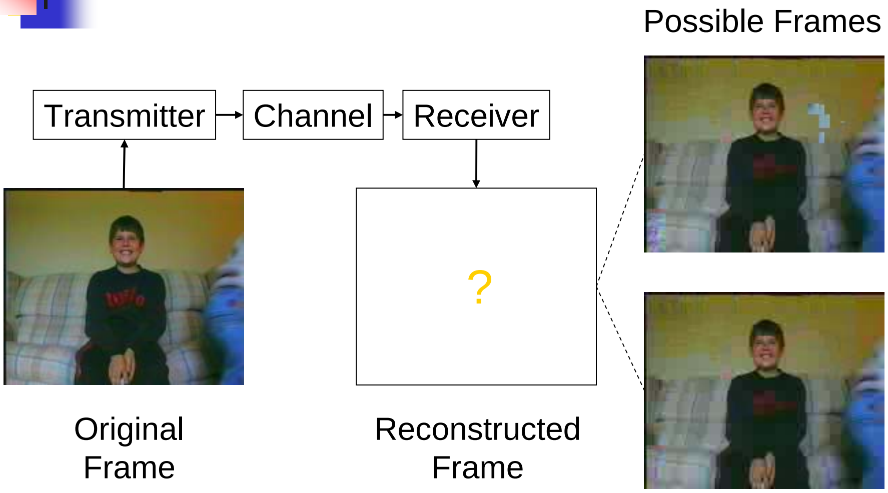


Resource Allocation for Frame 42

Frame 42



Is E[D] a Sufficient Quality Metric



Original Frame

Reconstructed Frame

Motivation

- Actual Distortion ≠ Expected Distortion

Expected Frame

Realization 1

Realization 2

Variance in Distortion

Variance in Distortion

Variance in Distortion if **Received**

Variance in Distortion if **Lost**

Difference in Expected Distortion if **Received** and **Lost**

$$Var[\mathrm{D}] = (1-\rho)Var[\mathrm{D_R}] + (\rho)Var[\mathrm{D_L}] + (1-\rho)(\rho)\big[E[\mathrm{D_R}] - E[\mathrm{D_L}]\big]^2$$

- Effect of Mode Selection on the Variance
  - Intra (I) Mode has $Var[D_R] = 0$
  - Inter (P) Mode has $Var[D_R] \geq 0$

VAPOR

Goal: Account for both the **mean** and **variance** in distortion when allocating resources.

$$\min_{\{S,P\}} \ (1-\alpha)\overset{\text{mean}}{\overset{\downarrow}{E[D]}}+(\alpha)\overset{\text{variance}}{\overset{\downarrow}{Std[D]}}$$

End-to-End Distortion

$$\text{s.t.}: \ T_{tot}\left(S,P\right)\leq T_{\max}$$

Transmission Delay Constraint

$$C_{tot}\left(S,P\right)\leq C_{\max}$$

Transmission Cost Constraint

Y. Eisenberg, et al, **"VAPOR: Variance-Aware Per-pixel Optimal Resource allocation,"** *IEEE Transactions on Image Processing*, vol. 15, issue 2, 289-299, February 2006.

Solution Approach

- Algorithm from Part I
  - Lagrange Relaxation
  - Dynamic Programming
  - Generalized Skip

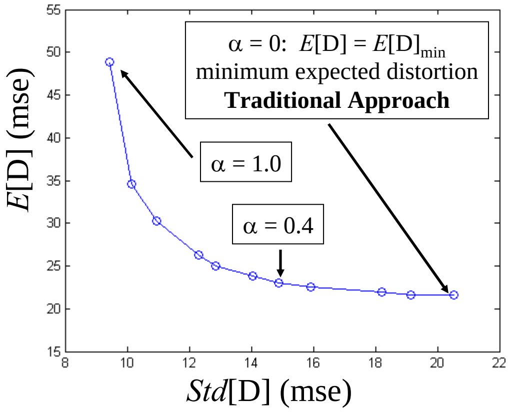
- New Distortion Metric

$$J_{tot}=(1-\alpha)E[D]+(\alpha)Std[D]+\lambda_1 T_{tot}+\lambda_2 \mathrm{E}_{tot}$$

Single Frame: Mean vs. Variance

$$\min\,(1-\alpha)E[\mathrm{D}]+(\alpha)Std[\mathrm{D}]$$

weighted sum of the mean and variance $\alpha \in [0,1]$



α = 0: E[D] = $E[\mathrm{D}]_{\min}$
minimum expected distortion
Traditional Approach

α = 1.0

α = 0.4

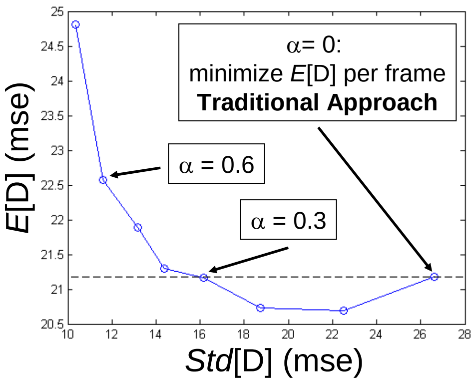
Observation:
possible to greatly reduce *Std*[D] with only a slight increase in *E*[D].

Consider α = 0.4
- 6% increase in *E*[D]
- 27% decrease in *Std*[D]

Example: frame 30 of the “Silent” Sequence; transmission rate = 150Kbps ; prob. of error = 0.01

Inter-Frame Interactions

values averaged over all frames



α= 0:
minimize *E*[D] per frame
Traditional Approach

α = 0.6

α = 0.3

- **Optimize One Frame at a Time**
  - Real-time communications
  - Complexity considerations
- **Effects of “VAPOR” on Sequence**
  - May actually reduce the average *E*[D] for the sequence
  - Greatly reduces the average *Std*[D] for the sequence

Example: Results for the “Silent” Sequence; *R* = 150 kbps ; prob. of error = 0.01

Experimental Results

Compare:

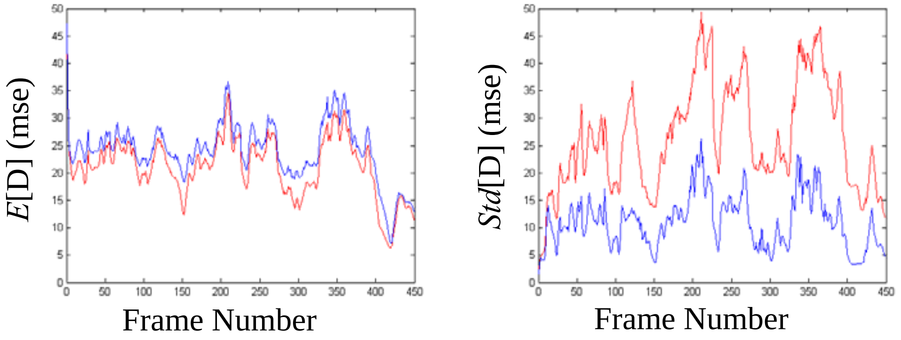
- VAPOR Approach
  - Minimize the mean and variance in distortion per frame
  - min $(1-\alpha)E[D] + (\alpha)Std[D]$; subject to: $B_{tot}(S) \leq B_{\max}$
- MED Approach
  - Minimize the expected distortion per frame
  - min $E[D]$; subject to: $B_{tot}(S) \leq B_{\max}$

Setup:

- Fixed Probability of Packet Loss ($\rho = 0.01$)
- Fixed Delay Constraint ($T_{\max} = 33$ ms)
- Fixed Transmission Rate ($R = 150$ kbps)
- Packetization: One MB per packet

Experimental Results

Results for the “**Silent**” Sequence: transmission rate = 150Kbps ; probability of error = 0.01



— VAPOR (Variance-Aware) — MED (Min *E*[D] Approach)	• VAPOR increases *E*[D] ≈ 12% • VAPOR decreases *Std*[D] ≈ 58%

Min E[D] Approach (MED)

VAPOR Approach

Channel Simulation #1

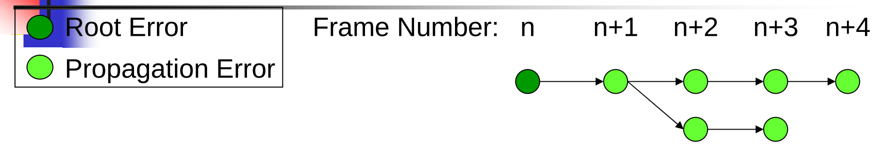
Channel Simulation #2

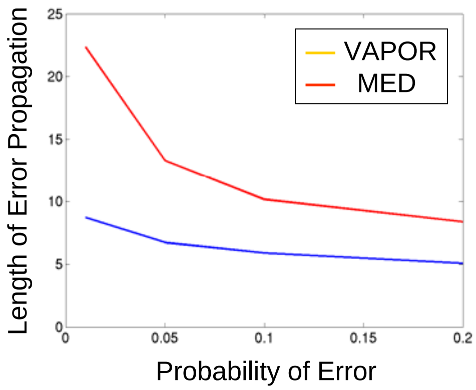
Summary - Part II

- Only One Reconstructed Sequence
  - actual distortion ≠ expected distortion
  - actual distortion ≈ expected distortion (desirable)

- Variance-Aware Resource Allocation
  - Prevents extreme distortion in localized regions
  - Reduces error propagation
  - Robust to Channel Mismatch

Channel Conditions and Error Propagation

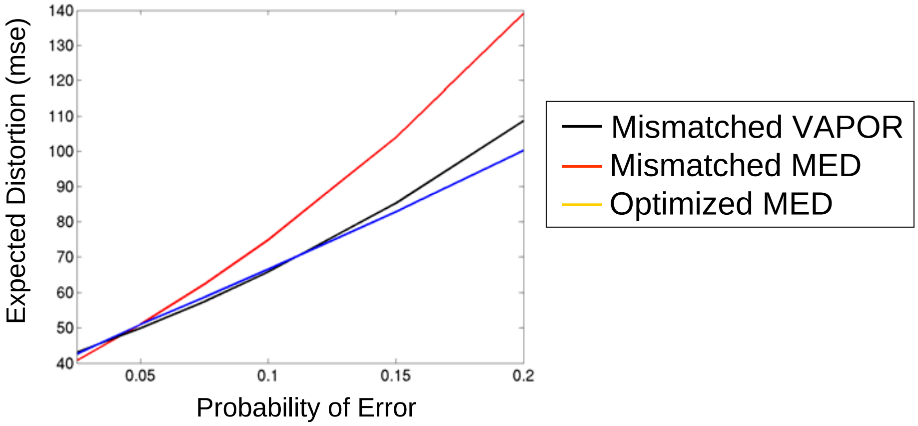




Low Probability of Error

- Desirable for communications
- May lead to large error propagation without VAPOR

Channel Mismatch Sensitivity



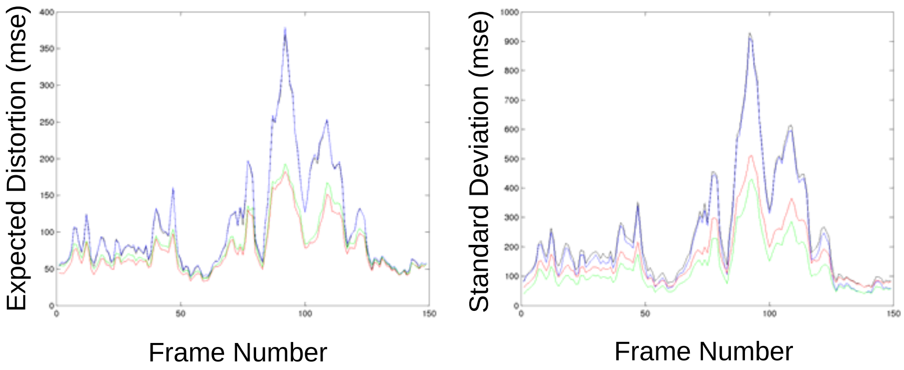
“Mismatched” schemes assume the Probability of Error = 0.05

“Optimized MED” approach is Optimized for each Probability of Error

Variable Power Experiments

— Fixed Power MED
— Fixed Power VAPOR

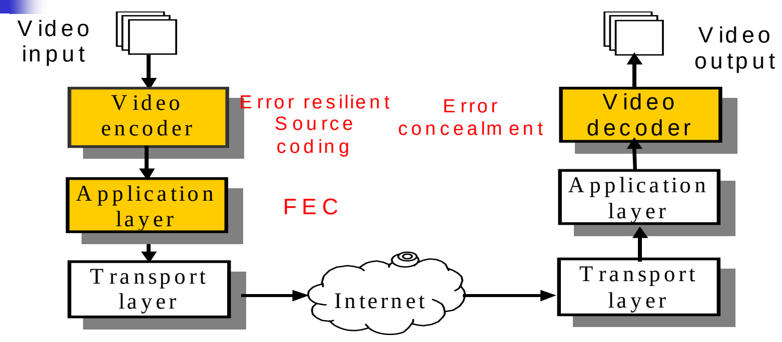
— Variable Power MED
— Variable Power VAPOR



CASE II

Summary of point-to-point problems

Internet Video Transmission



- ➢ We jointly consider error resilient source coding, FEC, and error concealment

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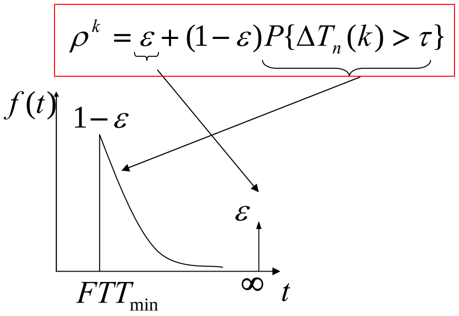
Channel Model

- Network model :

  an independent time-invariant packet erasure channel + random delays



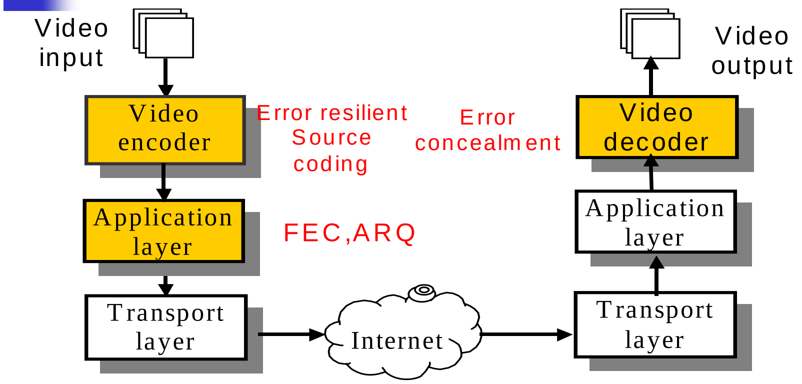
$$\rho^k = \underbrace{\varepsilon} + (1-\varepsilon)\underbrace{P\{\Delta T_n(k) > \tau\}}$$

- Packet delay
  - Exponential distribution: fast decaying tail
  - Gamma distribution
  - Pareto distribution: slowly decaying (heavy) tail
- Packet Loss
  - Bernoulli
  - 2-state Markov (Gilbert)
  - High-order Markov

FEC vs. ARQ

- FEC:
  - Usually preferred for real-time video applications
  - Cannot completely avoid packet loss
  - Incur constant overhead even when the channel has no loss
  - Depend on the accurate CSI estimation
- ARQ:
  - Can automatically adapt to the channel loss characteristics
  - Longer delay
  - Useful for long end-to-end delay applications, e.g., on-demand video streaming
  - Useful for short RTT situations, e.g., LAN

JSCC—Hybrid FEC/Retransmission



Video input

Video encoder

Error resilient Source coding

Application layer

FEC,ARQ

Transport layer

Internet

Error concealment

Transport layer

Application layer

Video decoder

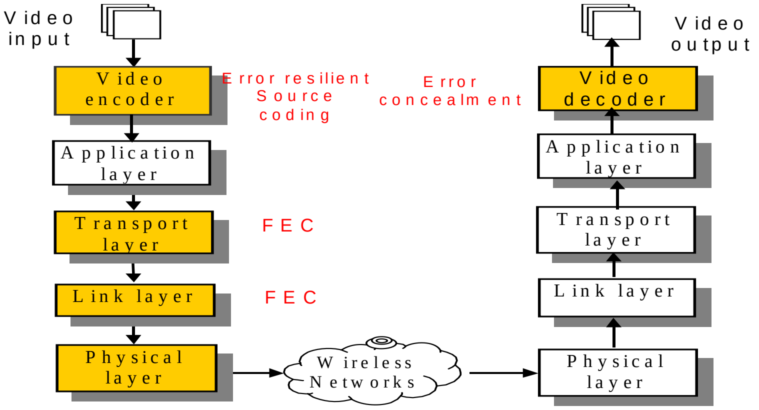
Video output

- We jointly consider error resilient source coding, FEC, application-layer ARQ, and error concealment

JSCC– Conclusions

- ➢ Retransmission is suitable for short network RTT, low probability of packet loss, and low transmission rate.
- ➢ FEC is more suitable otherwise.
- ➢ The proposed hybrid FEC/selective retransmission scheme outperforms both (average gain: 0.7 dB in PSNR).
- ➢ In our simulations, we assume the CSI is accurately estimated, which favors FEC, because ARQ does not require accurate CSI.

Hybrid Wireless Video Transmission



Video input

Video encoder

Application layer

Transport layer

Link layer

Physical layer

Error resilient Source coding

FEC

FEC

Wireless Networks

Error concealment

Video output

Video decoder

Application layer

Transport layer

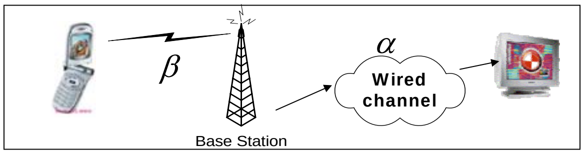
Link layer

Physical layer

Power control

- ➢ JSCCPA– Jointly Source-Channel Coding and Power Allocation

Hybrid Wireless Network



- At the IP level, the hybrid network can be modeled as the combination of two independent packet erasure channels: the wired part with loss rate α and the wireless part with loss rate β
- Overall probability of loss for a transport packet

$$\varepsilon_k = \alpha + (1-\alpha)\beta_k$$

- Probability of loss for a transport packet in the wireless channel

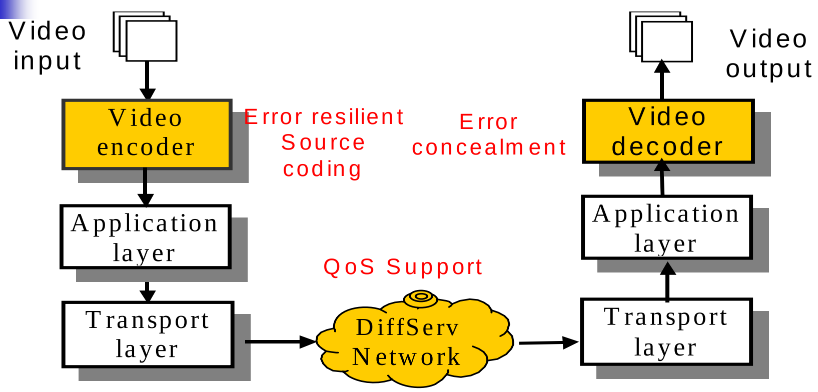
$$\beta_k(\mu_k, \nu_k, \eta_k) = 1 - (1 - p_b)^{B_k}$$

- We need Product FEC to combat different types of channel error

JSCCPA– Conclusions

- Optimal cross-layer resource allocation to provide UEP for wireless video transmission
    - Error resilient source coding
    - Transport-layer FEC
    - Link-layer FEC
    - Physical-layer power allocation
    - Error concealment
- Transport-layer FEC (inter-packet FEC) is not necessary if the wired link has no error.
- Adapting either power or link-layer FEC (instead both) may be adequate to achieve the near-optimal result in some situations.

DiffServ Video Transmission



- JSCPC– Jointly Source Coding and Packet Classification

F. Zhai, C. E. Luna, Y. Eisenberg, T. N. Pappas, R. Berry, A. K. Katsaggelos, “Joint source coding and packet classification for real-time video transmission over differentiated services networks,” *IEEE Trans. Multimedia*, 2004

Differentiated Services Networks

- Allocating resources discriminatorily to aggregated traffic flows
- Multiple service classes: different class has different end-to-end statistical behavior
- Sender is charged for each transmitted bit based on its service class