Encoder and Decoder Optimization for Source-Channel Prediction in Error Resilient Video Transmission

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Outline

- Background
- Source-channel prediction (SCP) encoder
- The matched SCP decoder
- Iterative SCP codec design
- Simulation results
- Summary + recent developments
Existing error resilient approaches to motion compensated prediction

- Multiple prediction threads
- Slicing
- Long-term memory motion compensation, multi-frame motion compensation
- And more…

Source-channel efforts mainly focused on mode selection, unequal error protection
Background

- Common to motion compensated prediction techniques:
  - Do not account for channel errors
  - Encoder reconstruction-based prediction

\[
\min_{\text{mv}} \sum_{i \in \text{MB}} \left( f_n^i - \hat{f}_{n-1}^{i+\text{mv}} \right)^2
\]

Motion estimation

\[
e_n^i = f_n^i - \hat{f}_{n-1}^{i+\text{mv}}
\]

Prediction residue

For pixel \( i \) in frame \( n \):

\( f_n^i, \hat{f}_n^i \) : Original and encoder reconstruction values

\( e_n^i \) : Prediction error
Source-Channel Prediction

- Proposed:
  - Joint source-channel approach
  - Prediction based on the expected decoder reconstruction

Motion estimation

\[
\min_{mv} \sum_{i \in MB} E \left\{ \left( f_n^i - \tilde{f}_{n-1}^{i+mv} \right)^2 \right\}
\]

Prediction residue

\[
e_n^i = f_n^i - E \left\{ \tilde{f}_{n-1}^{i+mv} \right\}
\]

For pixel \(i\) in frame \(n\):

\(\tilde{f}_n^i\) Decoder reconstruction value

(random variable for the encoder)
Source-Channel Prediction

- Crucial: accurate estimation of end-to-end quantities
  - Unlike more forgiving case of Inter/Intra mode selection
- Build on the technique:
  - Recursive optimal per-pixel estimate (ROPE) [Zhang et al. 00]
  - Originally proposed for optimal mode decisions

\[
E \{ \tilde{f}_n^i \} = (1 - p) \cdot \left( \hat{e}_n^i + E \{ \tilde{f}_{n-1}^{i+mv} \} \right) + p \cdot E \{ \tilde{f}_{n-1}^i \}
\]

- \( \hat{e}_n^i \) Quantized prediction error
- \( p \) Packet loss rate
- Similarly for second moments
Matched SCP Decoder

- Conventional decoder (assumed by SCP encoder):

  If packet received: \[ \tilde{f}_n^i = \tilde{f}_{n-1}^{i+mv} + \hat{e}_n^i \]

  If packet lost: \[ \tilde{f}_n^i = \tilde{f}_{n-1}^i \] Mismatch!

- Problem:

  SCP encoder reconstruction: \[ \hat{f}_n^i = E\{\tilde{f}_{n-1}^{i+mv}\} + \hat{e}_n^i \]

- Hence value of quantized residual is compromised

- Given \( p \) we propose a matched SCP decoder
Matched SCP Decoder

- The formulation:

If packet received:

\[
\tilde{f}_n^i = E \{ \tilde{f}_{n-1}^{i+mv} \} + \hat{e}_n^i
\]

\[
E \{ \tilde{f}_n^i \} = (1 - p) \cdot (\tilde{e}_n^i + E \{ \tilde{f}_{n-1}^{i+mv} \}) + p \cdot E \{ \tilde{f}_{n-1}^i \}
\]

If packet lost:

\[
\tilde{f}_n^i = \tilde{f}_{n-1}^i
\]

\[
E \{ \tilde{f}_n^i \} = (1 - p) \cdot \tilde{f}_{n-1}^i + p \cdot E \{ \tilde{f}_{n-1}^i \}
\]

Note error concealment effect, cannot reproduce

\[
E \{ \tilde{f}_{n-1}^{i+mv} \} + \hat{e}_n^i
\]

\[
E \{ \tilde{f}_n^i \} : \text{Decoder’s emulation of encoder’s}
\]

\[
E \{ \tilde{f}_n^i \}
\]
Iterative Design

- We may now revisit the SCP encoder, and in turn decoder...
- Iterated SCP codec optimization:

```
Conventional encoder  Conventional decoder
SCP encoder (1st)     SCP decoder (1st)
SCP encoder (2nd)     SCP decoder (2nd)
...                   ...
```
Iterative Design

- Unfortunately, complexity grows with additional design iterations.
  - More correlation terms involved (details omitted)

- Results show:
  - One complete round of SCP optimization offers significant gains.
  - Multiple re-optimization iterations provide only minor additional gains, while incurring a considerable increase in complexity.
Simulation Results

- Simulation conditions
  - UBC H.263+ codec
  - System performance measure: average luminance PSNR
  - 50 different packet loss patterns

- Testing scenarios
  - Periodic Intra updating: an MB is Intra coded once per 1/p frames
  - Optimal Intra updating: RD optimized Intra mode selection using ROPE.
Simulation Results

- Tested versions
  - SP codec: conventional encoder + conventional decoder (source-based prediction)
  - SCP1 enc: SCP encoder + conventional decoder
  - SCP1 codec: SCP encoder + SCP matched decoder
  - SCP2 enc: 2nd-round optimized SCP encoder + SCP matched decoder
  - SCP2 codec: 2nd-round optimized SCP encoder + 2nd-round matched SCP decoder
Simulation Results — Periodic Intra

Foreman: PSNR vs. packet loss rate.
QCIF, 10f/s, 48kb/s, 1st 200frames.
Simulation Results — Periodic Intra

Carphone: PSNR vs. packet loss rate. QCIF, 10f/s, 48kb/s, 1st 200 frames.
Simulation Results — Periodic Intra

Foreman: PSNR vs. total bit rate.
QCIF, 10f/s, p=0.1, 1st 200 frames.
Simulation Results — Periodic Intra

Carphone: PSNR vs. total bit rate.
QCIF, 10f/s, p=0.1, 1st 200 frames.
Simulation Result — Optimal Intra

Foreman: PSNR vs. packet loss rate.
QCIF, 10f/s, 48kb/s, 1st 200frames.
Simulation Result — Optimal Intra

Carphone: PSNR vs. packet loss rate.
QCIF, 10f/s, 48kb/s, 1st 200frames.
Simulation Results — Optimal Intra

[Graph showing PSNR vs. total bit rate for different codecs: SP codec, SCP1 enc, SCP1 codec.]

Foreman: PSNR vs. total bit rate.
QCIF, 10f/s, p=0.1, 1st 200 frames.
Carphone: PSNR vs. total bit rate.
QCIF, 10f/s, p=0.1, 1st 200 frames.
Summary

- Source-channel prediction: The ROPE-based SCP encoder and its matching decoder

- Iterative SCP design

- One complete iteration of SCP design offers significant gains.

- Simulations suggest that multiple-round optimization is not cost-effective - offers minor additional gains, and involves a considerable complexity increase.
Recent Developments

- There seems to be a way to obtain non trivial gains from more design iterations at low complexity by changing the conventional concealment rule at the matched decoder.

- Work in progress to incorporate SCP motion compensation/prediction within overall rate distortion framework at moderate complexity.
Thanks!
The encoder: assuming the SCP matched decoder

\[ E \{ \tilde{f}_n^i \} = (1 - p) \cdot (\hat{e}_n^i + E \{ E \{ \tilde{f}_{n-1}^{i+mv} \}_d \}) + p \cdot E \{ \tilde{f}_{n-1}^i \} \]

\[ E \{ E \{ \tilde{f}_n^i \}_d \} = (1 - p) \cdot [(1 - p) \cdot (\hat{e}_n^i + E \{ E \{ \tilde{f}_{n-1}^{i+mv} \}_d \})] + p \cdot E \{ E \{ \tilde{f}_{n-1}^i \}_d \} \]

\[ + p \cdot [(1 - p) \cdot E \{ \tilde{f}_{n-1}^i \} + p \cdot E \{ E \{ \tilde{f}_{n-1}^i \}_d \}] \]

- \( E \{ \tilde{f}_n^i \}_d \) is a random variable for the encoder.
- \( E \left( \left( E \{ \tilde{f}_n^i \}_d \right)^2 \right) \) involves cross-correlation terms. To estimate them with tractable complexity, the estimation accuracy have to be slightly compromised [Yang 03].
The 2nd-Round Optimized SCP Codec

The matched decoder

If packet received:

\[
\{ \tilde{f}_n^i \}_d = (1 - p) \cdot (\hat{e}_n^i + E \{ E \{ \tilde{f}_{n-1}^{i+mv} \}_d \}_d) + p \cdot E \{ \tilde{f}_{n-1}^i \}_d
\]

\[
E \{ E \{ \tilde{f}_n^i \}_d \}_d = (1 - p) \cdot [ (1 - p) \cdot (\hat{e}_n^i + E \{ E \{ \tilde{f}_{n-1}^{i+mv} \}_d \}_d) + p \cdot E \{ E \{ \tilde{f}_{n-1}^i \}_d \}_d ]
\]

\[
+ p \cdot [ (1 - p) \cdot E \{ \tilde{f}_{n-1}^i \}_d + p \cdot E \{ E \{ \tilde{f}_{n-1}^i \}_d \}_d ]
\]

If packet lost:

\[
E \{ \tilde{f}_n^i \}_d = (1 - p) \cdot X_2 + p \cdot E \{ \tilde{f}_{n-1}^i \}_d
\]

\[
E \{ E \{ \tilde{f}_n^i \}_d \}_d = (1 - p) \cdot [(1 - p) \cdot X_2 + p \cdot E \{ E \{ \tilde{f}_{n-1}^i \}_d \}_d ]
\]

\[
+ p \cdot [ (1 - p) \cdot E \{ \tilde{f}_{n-1}^i \}_d + p \cdot E \{ E \{ \tilde{f}_{n-1}^i \}_d \}_d ]
\]
The 2nd-Round Optimized SCP Codec

- The matched decoder (cont.)
  
  For error concealment of $\hat{e}_n^i + E\left\{E\left\{\tilde{f}_{n-1}^{i+mv}\right\}_d\right\}_d$, $X_2 = E\left\{E\left\{f_{n-1}^i\right\}_d\right\}_d$

  $$E\left\{E\left\{f_n^i\right\}_d\right\}_d$$ _decoder's emulation of encoder's  $E\left\{f_n^i\right\}_d$

- Similarly, more rounds of SCP optimization incur more complexity, esp. for the encoder, as more cross-correlation terms will be involved.