

Prediction Residue Analysis in MPEG-2 Double Compressed Video Sequences

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Motivation and Objectives

Motivation

Nowadays, **video sequences** are no longer more difficult to tamper with than digital images.

Example: DeepFakes



Real?



Fake?



Real?



Fake?

Our goal

- **In-depth analysis** of the prediction residue in double compressed videos
- **Evaluate the effect** of certain video coding parameters:
 - Quantizer **deadzone** width
- **Predict** the behavior of some video forensics tools, such as those based on the VPF

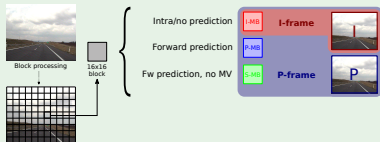
Basics on Video Coding

Basic concepts

Group of Pictures (GOP):

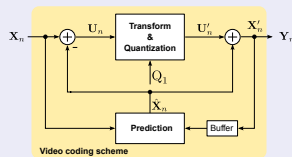


MacroBlock (MB) types:



Our modeling

Single compression scheme:



Prediction:

$$\hat{\mathbf{X}}_n = \begin{cases} 0, & \text{if } \text{I-MB} \\ \mathbf{X}'_{n-1}(\mathbf{m}), & \text{if } \text{P-MB} \\ \mathbf{X}'_{n-1}, & \text{if } \text{S-MB} \end{cases}$$

Residue: $\mathbf{U}_n = \mathbf{X}_n - \hat{\mathbf{X}}_n \rightarrow \text{DCT}$

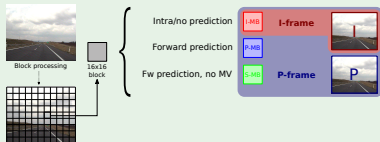
Basics on Video Coding

Basic concepts

Group of Pictures (GOP):

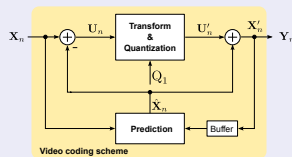


MacroBlock (MB) types:

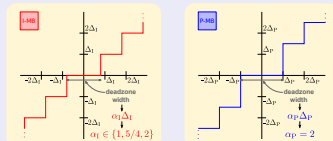


Our modeling

Single compression scheme:



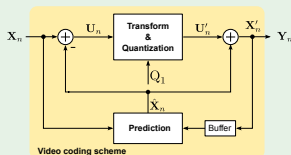
Quantization:



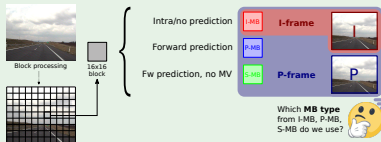
Basics on Video Coding

Basic concepts

Single compression scheme:



MacroBlock (MB) types:



Video coding strategy

Coding problem: minimize distortion up to a maximum rate r :

$$\begin{aligned} &\text{minimize} && D(\mathbf{X}_n, \mathbf{X}'_n) \\ &\text{subject to} && R(\mathbf{X}'_n) \leq r \end{aligned}$$

Best solution: Lagrangian-based optimization with λ :

$$\text{minimize} \quad D(\mathbf{X}_n, \mathbf{X}'_n) + \lambda R(\mathbf{X}'_n)$$

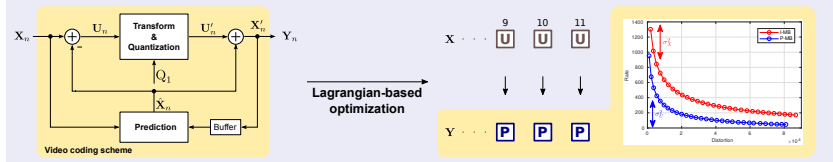
MB type selection criteria:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{X}_n, \mathbf{X}'_n) + \lambda_c R(\mathbf{X}'_n)$$

where $\mathcal{C} = \{\text{I-MB}, \text{P-MB}, \text{S-MB}\}$.

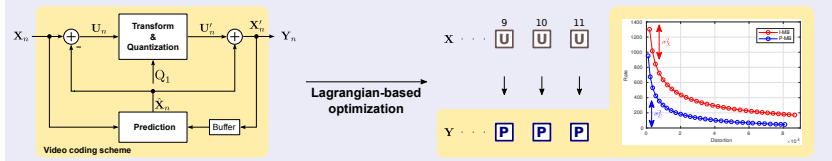
Single vs. Double compression

Single compression scheme

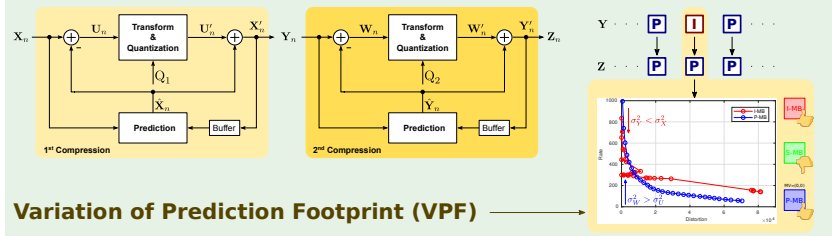


Single vs. Double compression

Single compression scheme

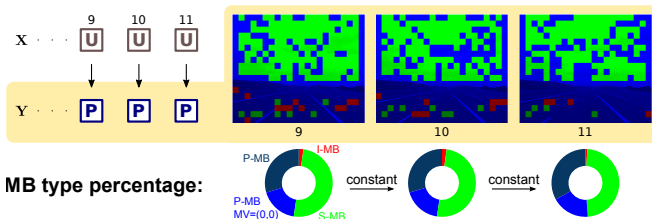


Double compression scheme

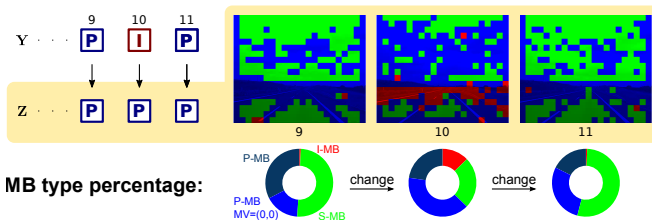


VPF analysis with a real example (I)

Single compression:

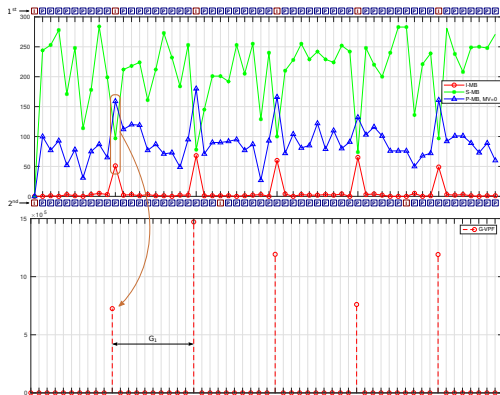


Double compression: ($G_1 = 10$, $G_2 = 33$)



VPF analysis with a real example (II)

Double compression: ($G_1 = 10$, $G_2 = 33$)



B-VPF method*

- I-MB
- S-MB

G-VPF method†

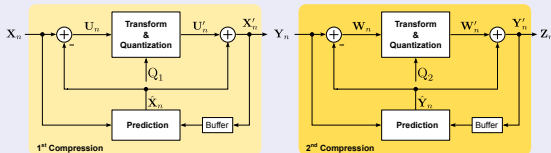
- I-MB
- S-MB
- P-MB,
MV=(0,0)

* Vázquez-Padín *et al.*, "Detection of video double encoding with GOP size estimation" in Proc. of the 4th IEEE International Workshop on Information Forensics and Security (WIFS), December 2012, pp. 151-156.

† Vázquez-Padín *et al.*, "Video integrity verification and GOP size estimation via generalized variation of prediction footprint," 2019 (submitted).

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

Distortion:

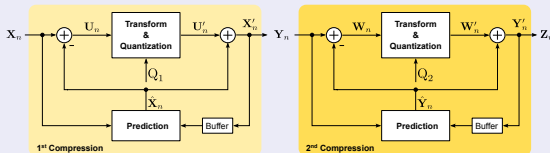
$$\begin{aligned} D(\mathbf{Y}_n, \mathbf{Y}'_n) &\triangleq \|\mathbf{Y}_n - \mathbf{Y}'_n\|_2^2 \\ &= \|\mathbf{W}_n + \hat{\mathbf{Y}}_n - (\mathbf{W}'_n + \hat{\mathbf{Y}}_n)\|_2^2 \\ &= \|\mathbf{W}_n - \mathbf{W}'_n\|_2^2 \end{aligned}$$

VPF strength depends on $\longrightarrow$

$$\text{Var}(\mathbf{W}_n) \Big|_{\substack{\uparrow \\ \downarrow}} - \text{Var}(\mathbf{W}_n) \Big|_{\substack{\uparrow \\ \downarrow}}$$

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

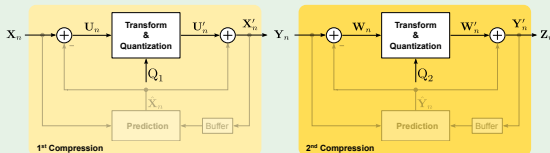
Distortion:

$$\begin{aligned} D(\mathbf{Y}_n, \mathbf{Y}'_n) &\triangleq \|\mathbf{Y}_n - \mathbf{Y}'_n\|_2^2 \\ &= \|\mathbf{W}_n + \hat{\mathbf{Y}}_n - (\mathbf{W}'_n + \hat{\mathbf{Y}}_n)\|_2^2 \\ &= \|\mathbf{W}_n - \mathbf{W}'_n\|_2^2 \end{aligned}$$

VPF strength depends on →

$$\text{Var}(\mathbf{W}_n) \Big|_{\frac{1}{4}} - \text{Var}(\mathbf{W}_n) \Big|_{\frac{1}{2}}$$

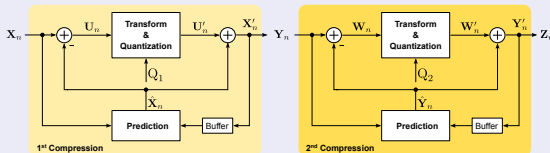
Intra-prediction residue analysis: I-frame in 1st compression



$$\begin{aligned} \text{Var}(\mathbf{W}_n) \Big|_{\frac{1}{4}} &= \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{11}) \\ \text{Var}(\mathbf{E}_n^{11}) &\propto D(\mathbf{X}_n, \mathbf{X}'_n) \leftarrow \mathbf{X}'_n - \mathbf{X}_n \end{aligned}$$

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

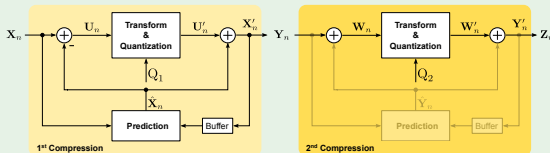
Distortion:

$$\begin{aligned} D(\mathbf{Y}_n, \mathbf{Y}'_n) &\triangleq \|\mathbf{Y}_n - \mathbf{Y}'_n\|_2^2 \\ &= \|\mathbf{W}_n + \hat{\mathbf{Y}}_n - (\mathbf{W}'_n + \hat{\mathbf{Y}}_n)\|_2^2 \\ &= \|\mathbf{W}_n - \mathbf{W}'_n\|_2^2 \end{aligned}$$

VPF strength depends on $\longrightarrow$

$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} - \text{Var}(\mathbf{W}_n) \Big|_{\mathcal{P}}$$

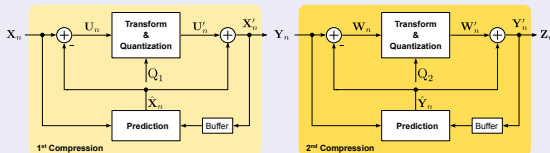
Intra-prediction residue analysis: P-frame in 1st compression



$$\begin{aligned} \text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} &= \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{I_1}) \\ \text{Var}(\mathbf{E}_n^{I_1}) &\propto D(\mathbf{X}_n, \mathbf{X}'_n) \quad U'_n = U_n \\ \text{Var}(\mathbf{W}_n) \Big|_{\mathcal{P}} &= \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{P_1}) \\ \text{Var}(\mathbf{E}_n^{P_1}) &\propto p(\mathcal{D})D(U_n, U'_n) \\ &\quad + p(\mathcal{D})D(\mathbf{X}_n, \mathbf{X}'_{n-1}) + p(\mathcal{D})D(\mathbf{X}_n, \mathbf{X}'_n) \end{aligned}$$

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

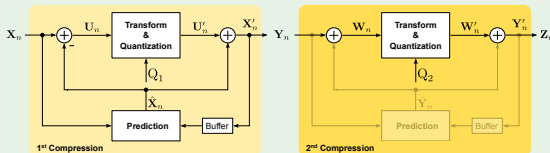
Distortion:

$$\begin{aligned} D(\mathbf{Y}_n, \mathbf{Y}'_n) &\triangleq \|\mathbf{Y}_n - \mathbf{Y}'_n\|_2^2 \\ &= \|\mathbf{W}_n + \hat{\mathbf{Y}}_n - (\mathbf{W}'_n + \hat{\mathbf{Y}}_n)\|_2^2 \\ &= \|\mathbf{W}_n - \mathbf{W}'_n\|_2^2 \end{aligned}$$

VPF strength depends on →

$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} - \text{Var}(\mathbf{W}_n) \Big|_{\mathcal{P}}$$

Intra-prediction residue analysis: P-frame in 1st compression



$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} = \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{I_1})$$

$$\text{Var}(\mathbf{E}_n^{I_1}) \propto D(\mathbf{X}_n, \mathbf{X}'_n)$$

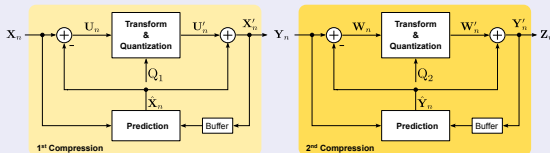
$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{P}} = \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{P_1})$$

$$\text{Var}(\mathbf{E}_n^{P_1}) \propto D(\mathbf{U}_n, \mathbf{U}'_n)$$

Dynamic video → $p(\text{blue}) \gg p(\text{green}) + p(\text{red})$

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

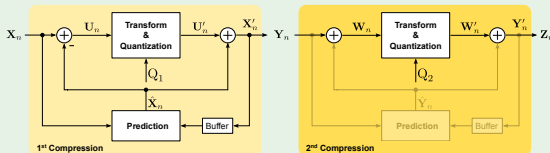
Distortion:

$$\begin{aligned} D(\mathbf{Y}_n, \mathbf{Y}'_n) &\triangleq \|\mathbf{Y}_n - \mathbf{Y}'_n\|_2^2 \\ &= \|\mathbf{W}_n + \hat{\mathbf{Y}}_n - (\mathbf{W}'_n + \hat{\mathbf{Y}}_n)\|_2^2 \\ &= \|\mathbf{W}_n - \mathbf{W}'_n\|_2^2 \end{aligned}$$

VPF strength depends on →

$$\text{Var}(\mathbf{W}_n) \Big|_{\mathbb{P}} - \text{Var}(\mathbf{W}_n) \Big|_{\mathbb{P}}$$

Intra-prediction residue analysis: P-frame in 1st compression



$$\text{Var}(\mathbf{W}_n) \Big|_{\mathbb{P}} = \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{I_1})$$

$$\text{Var}(\mathbf{E}_n^{I_1}) \propto D(\mathbf{X}_n, \mathbf{X}'_n)$$

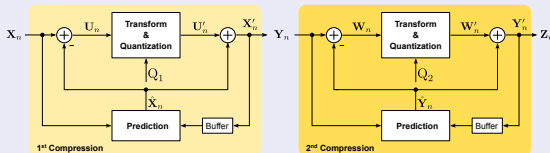
$$\text{Var}(\mathbf{W}_n) \Big|_{\mathbb{P}} = \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{P_1})$$

$$\text{Var}(\mathbf{E}_n^{P_1}) \propto D(\mathbf{X}_n, \mathbf{X}'_{n-1})$$

Static video → $p(\text{green}) \gg p(\text{blue}) + p(\text{red})$

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

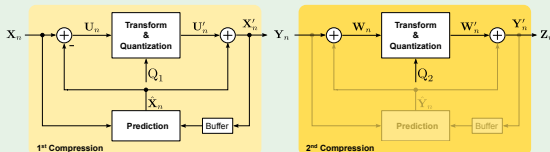
Distortion:

$$\begin{aligned} D(\mathbf{Y}_n, \mathbf{Y}'_n) &\triangleq \|\mathbf{Y}_n - \mathbf{Y}'_n\|_2^2 \\ &= \|\mathbf{W}_n + \hat{\mathbf{Y}}_n - (\mathbf{W}'_n + \hat{\mathbf{Y}}_n)\|_2^2 \\ &= \|\mathbf{W}_n - \mathbf{W}'_n\|_2^2 \end{aligned}$$

VPF strength depends on $\longrightarrow$

$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} - \text{Var}(\mathbf{W}_n) \Big|_{\mathcal{B}}$$

Intra-prediction residue analysis: P-frame in 1st compression



$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} = \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{I_1})$$

$$\text{Var}(\mathbf{E}_n^{I_1}) \propto D(\mathbf{X}_n, \mathbf{X}'_n)$$

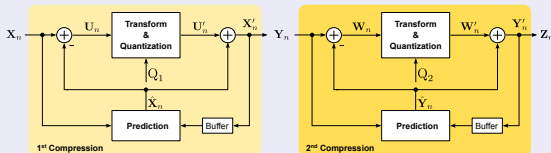
$$\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{B}} = \text{Var}(\mathbf{X}_n) + \text{Var}(\mathbf{E}_n^{P_1})$$

$$\text{Var}(\mathbf{E}_n^{P_1}) \propto D(\mathbf{X}_n, \mathbf{X}'_{n-1})$$

Static video $\text{Var}(\mathbf{W}_n) \Big|_{\mathcal{D}} \approx \text{Var}(\mathbf{W}_n) \Big|_{\mathcal{B}}$

Prediction Residue Analysis (I)

Double compression scheme



MB type:

$$\arg \min_{c \in \mathcal{C}} D(\mathbf{Y}_n, \mathbf{Y}'_n) + \lambda_c R(\mathbf{Y}'_n)$$

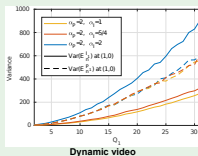
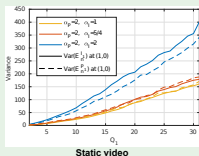
Distortion:

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VPF strength depends on $\longrightarrow$

$$\text{Var}(\mathbf{W}_n) \Big|_{\frac{1}{4}} - \text{Var}(\mathbf{W}_n) \Big|_{\frac{1}{8}}$$

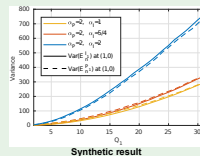
Intra-prediction residue analysis



Semi-analytic model:

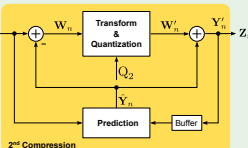
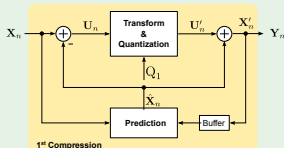
- $\longrightarrow$ Laplacian signals
- $\longrightarrow$ AR model for temporal dependencies

(only valid for modeling static videos)



Prediction Residue Analysis (II)

Inter-prediction residue analysis



Prediction residue (w/o Q):

$$R_n \triangleq X_n - X_{n-1}(m)$$

Quantization errors:

$$E_{n-1}^{P_1} \triangleq U'_{n-1}(m) - U_{n-1}(m)$$

$$E_{n-1}^{P_2} \triangleq W'_{n-1}(m) - W_{n-1}(m)$$

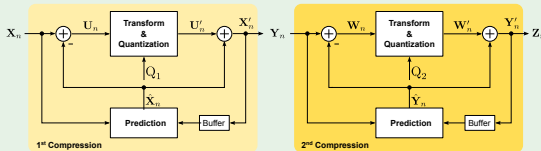
Prediction residue (w/ Q):

$$W_n = R_n + E_n, \quad E_n = \begin{cases} E_n^{I_1} - E_{n-1}^{P_1} - E_{n-1}^{P_2}, & \text{if } \boxed{\text{red}} \rightarrow \boxed{\text{blue}} \\ E_n^{P_1} - E_{n-1}^{P_1} - E_{n-1}^{P_2}, & \text{if } \boxed{\text{blue}} \rightarrow \boxed{\text{blue}} \end{cases}$$

$$\begin{aligned} \text{Var}(W_n) \Big|_{\boxed{\text{red}} \rightarrow \boxed{\text{blue}}} - \text{Var}(W_n) \Big|_{\boxed{\text{blue}} \rightarrow \boxed{\text{blue}}} &= \underbrace{\text{Var}(E_n^{I_1}) - \text{Var}(E_n^{P_1}) - 2(\text{cov}(E_n^{I_1}, E_{n-1}^{P_1}) - \text{cov}(E_n^{P_1}, E_{n-1}^{P_1}))}_{\text{depends on } Q_1} \\ &\quad - \underbrace{2(\text{cov}(E_n^{I_1}, E_{n-1}^{P_2}) - \text{cov}(E_n^{P_1}, E_{n-1}^{P_2}))}_{\text{depends on } Q_1 \text{ and } Q_2} \end{aligned}$$

Prediction Residue Analysis (II)

Inter-prediction residue analysis



Prediction residue (w/o Q):

$$R_n \triangleq X_n - X_{n-1}(m)$$

Quantization errors:

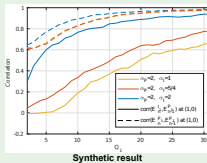
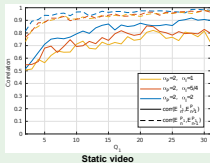
$$E_{n-1}^{P_1} \triangleq U'_{n-1}(m) - U_{n-1}(m)$$

$$E_{n-1}^{P_2} \triangleq W'_{n-1}(m) - W_{n-1}(m)$$

Prediction residue (w/ Q):

$$W_n = R_n + E_n, \quad E_n = \begin{cases} E_n^{I_1} - E_{n-1}^{P_1} - E_{n-1}^{P_2}, & \text{if } \boxed{\text{I}} \rightarrow \boxed{\text{I}} \\ E_n^{P_1} - E_{n-1}^{P_1} - E_{n-1}^{P_2}, & \text{if } \boxed{\text{I}} \rightarrow \boxed{\text{P}} \end{cases}$$

$$\begin{aligned} \text{Var}(W_n) \Big|_{\boxed{\text{I}} \rightarrow \boxed{\text{I}}} - \text{Var}(W_n) \Big|_{\boxed{\text{I}} \rightarrow \boxed{\text{P}}} &= \underbrace{\text{Var}(E_n^{I_1}) - \text{Var}(E_n^{P_1}) - 2(\text{cov}(E_n^{I_1}, E_{n-1}^{P_1}) - \text{cov}(E_n^{P_1}, E_{n-1}^{P_1}))}_{\text{depends on } Q_1} \\ &\quad - \underbrace{2(\text{cov}(E_n^{I_1}, E_{n-1}^{P_2}) - \text{cov}(E_n^{P_1}, E_{n-1}^{P_2}))}_{\text{depends on } Q_1 \text{ and } Q_2} \end{aligned}$$



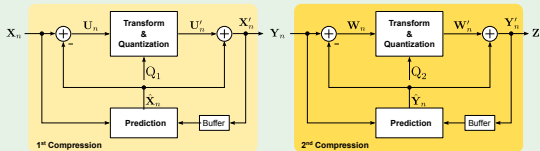
Nearly constant for distinct values of Q_1, α_I, α_P



No prominent changes in $\text{Var}(W_n) \Big|_{\boxed{\text{I}} \rightarrow \boxed{\text{I}}} - \text{Var}(W_n) \Big|_{\boxed{\text{I}} \rightarrow \boxed{\text{P}}}$

Prediction Residue Analysis (II)

Inter-prediction residue analysis



Prediction residue (w/o Q):

$$R_n \triangleq X_n - X_{n-1}(m)$$

Quantization errors:

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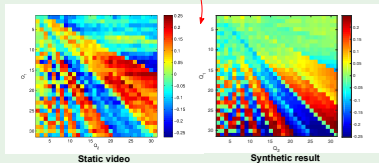
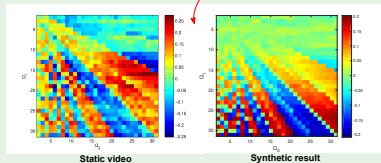
Prediction residue (w/ Q):

$$W_n = R_n + E_n, \quad E_n = \begin{cases} E_n^{I_1} - E_{n-1}^{P_1} - E_{n-1}^{P_2}, & \text{if } \boxed{\square} \rightarrow \boxed{\square} \\ E_n^{P_1} - E_{n-1}^{P_1} - E_{n-1}^{P_2}, & \text{if } \boxed{\square} \rightarrow \boxed{\square} \end{cases}$$

$$\text{Var}(W_n) \Big|_{\boxed{\square}} - \text{Var}(W_n) \Big|_{\boxed{\square}} = \underbrace{\text{Var}(E_n^{I_1}) - \text{Var}(E_n^{P_1}) - 2(\text{cov}(E_n^{I_1}, E_{n-1}^{P_1}) - \text{cov}(E_n^{P_1}, E_{n-1}^{P_1}))}_{\text{depends on } Q_1} - \underbrace{2(\text{cov}(E_n^{I_1}, E_{n-1}^{P_2}) - \text{cov}(E_n^{P_1}, E_{n-1}^{P_2}))}_{\text{depends on } Q_1 \text{ and } Q_2}$$

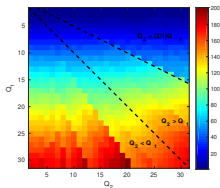
$\alpha_I = 1$
 $\alpha_P = 2$

$\alpha_I = 1$
 $\alpha_P = 2$

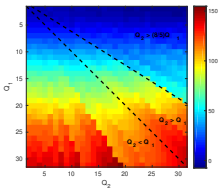


Prediction Residue Analysis (III)

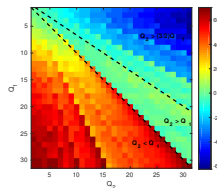
Evolution of $\text{Var}(\mathbf{W}_n) \Big|_{\substack{\mathbf{I} \\ \mathbf{P}}} - \text{Var}(\mathbf{W}_n) \Big|_{\substack{\mathbf{P} \\ \mathbf{P}}}$



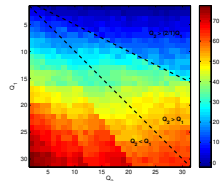
(a) Synthetic ($\alpha_I = 1$, $\alpha_P = 2$)



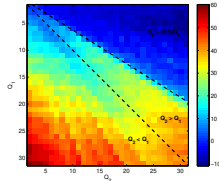
(b) Synthetic ($\alpha_I = \frac{5}{4}$, $\alpha_P = 2$)



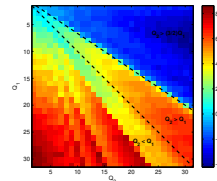
(c) Synthetic ($\alpha_I = 2$, $\alpha_P = 2$)



(d) Static videos ($\alpha_I = 1$, $\alpha_P = 2$)



(e) Static videos ($\alpha_I = \frac{5}{4}$, $\alpha_P = 2$)



(f) Static videos ($\alpha_I = 2$, $\alpha_P = 2$)

Experimental Setup

Dataset

- 14 CIF resolution videos from **Derf's collection** [xiph.org]

Benchmark methods

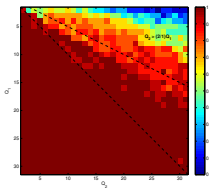
- **G-VPF**: improved VPF acquisition through P-MBs with $MV = (0, 0)$
- **B-VPF**: baseline VPF-based method

Testing parameters

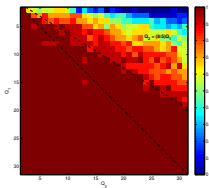
- **Quantization**: fixed (Q_1, Q_2) pairs with $Q_1, Q_2 \in \{2, \dots, 31\}$
- **Deadzone widths**: $\alpha_I \in \{1, 5/4, 2\}$, $\alpha_P = 2$
- **Encoders**: MPEG-2, but also MPEG-4 and H.264
- **GOPs**: $G_1 = 10$, $G_2 = 33$

Experimental Results (I)

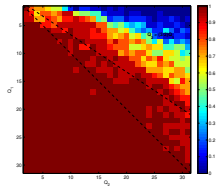
GOP size estimation: Exact Match Rate (EMR) between G_1 and $\hat{G}_1$



(a) G-VPF ($\alpha_I = 1$, $\alpha_P = 2$)



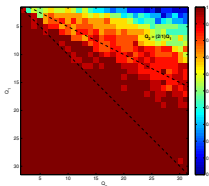
(b) G-VPF ($\alpha_I = 5/4$, $\alpha_P = 2$)



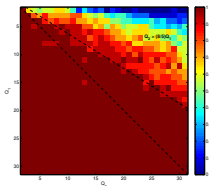
(c) G-VPF ($\alpha_I = \frac{5}{4}$, $\alpha_P = 2$)

Experimental Results (I)

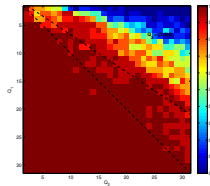
GOP size estimation: Exact Match Rate (EMR) between G_1 and $\hat{G}_1$



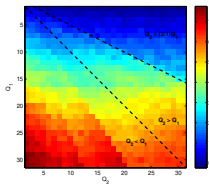
(a) G-VPF ($\alpha_I = 1$, $\alpha_P = 2$)



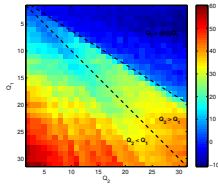
(b) G-VPF ($\alpha_I = 5/4$, $\alpha_P = 2$)



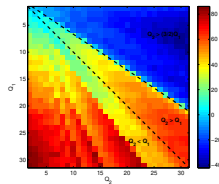
(c) G-VPF ($\alpha_I = \frac{5}{4}$, $\alpha_P = 2$)



(d) Static videos ($\alpha_I = 1$, $\alpha_P = 2$)



(e) Static videos ($\alpha_I = \frac{5}{4}$, $\alpha_P = 2$)



(f) Static videos ($\alpha_I = 2$, $\alpha_P = 2$)

Experimental Results (II)

Global EMR and Double compression detection: comparative results

EMR								
α_l	MPEG-2		MPEG-4		H.264		MPEG-2 (G-VPF)	
	G-VPF	B-VPF	G-VPF	B-VPF	G-VPF	B-VPF	Static	Dynamic
1	0.9111	0.6835	0.9065	0.6557	0.7262	0.6967	0.9632	0.8173
$\frac{5}{4}$	0.9063	0.7150	0.9079	0.6942	0.7274	0.6984	0.9444	0.8378
2	0.8630	0.7699	0.8826	0.7978	0.7399	0.6874	0.8651	0.8592
AUC								
α_l	MPEG-2		MPEG-4		H.264		MPEG-2 (G-VPF)	
	G-VPF	B-VPF	G-VPF	B-VPF	G-VPF	B-VPF	Static	Dynamic
1	0.9632	0.8406	0.9509	0.8073	0.8556	0.8589	0.9872	0.9259
$\frac{5}{4}$	0.9588	0.8540	0.9572	0.8306	0.8589	0.8603	0.9733	0.9254
2	0.9243	0.8930	0.9382	0.8952	0.8743	0.8443	0.9111	0.9129

Conclusions

Key aspects of our work

- **In-depth** analysis of the prediction residue in video coding
- Derivation of a **semi-analytic model** to predict the VPF behavior
- **Explanation** of why the VPF shows up and its **dependence** with:
 - **Quantization parameters** during both compressions
 - **Deadzone widths** for quantization

Future research work

- **Review** the derived model and **extend** it to MPEG-4 and H.264
- Address **more complex coding settings**:
 - Include **B-frames**
 - **Adaptive bitrate** control
- Derive **closed-form expressions** from the semi-analytic model

Thanks for your attention!

Questions?

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