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Author: Hunter Kippen

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New Methods for Detecting Frame Deletion in Modern Video

A Thesis

Submitted to the Faculty

of

Drexel University

by

Hunter Kippen

in partial fulfillment of the

requirements for the degree

of

Master of Science

May 2019

Dedications

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Abstract

New Methods for Detecting Frame Deletion in Modern Video
Hunter Kippen
Dr. Matthew Stamm, Ph.D.

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Chapter 1: Problem Formulation

Detecting frame deletion in a video requires detecting the structural changes in a video due to the deletion process. In particular, Wang and Farid's work on temporal traces for detecting frame deletion shows that for MPEG-2 video, the P-frame prediction error can be formulated into a sequence. This sequence can then be monitored to detect frame deletion. Both Wang and Farid, and Stamm et al. use a system like in Fig. 1.1 to detect frame deletion. The prediction error sequence $e(n)$ is extracted from the decoded video file and processed to produce detection features. Wang and Farid's work did not propose features for automatic detection, and instead relied on visual inspection of the DFT of the prediction error sequence [1] [2].

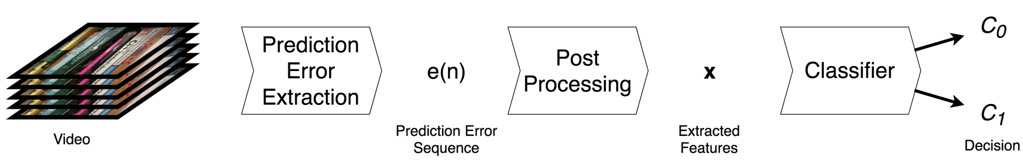


Figure 1.1: Generalized Approach to Frame Deletion Detection

This broad approach can also be applied to work with H.264 encoded video as well. While video encoding has advanced significantly, the fundamental structures of a compressed digital video have remained unchanged. Regardless of codec, the hallmark of video compression is the motion compensation and estimation process. Video frames are organized into GOPs that begin with an I-frame, and have varying structures of P and B-frames. In H.264, GOP structures are more dynamic due to the ability to derive motion-vector predictions from across multiple anchor frames. To remain robust to these advances in video compression, the prediction error extraction and post processing steps must be altered or augmented.

This work is concerned particularly with the detection of frame deletion in H.264 and similar modern video codecs. Frame addition has also been observed to introduce similar traces in the P-frame prediction error sequence as frame deletion. Our proposed system can be applied to detecting frame addition and for simplicity we will not discuss the detection of frame addition for the remainder of this thesis. We have made the following assumptions regarding our proposed system. First, we assume that all altered video has undergone re-compression. In fact, since most consumer video recording devices do not have the storage capability or processing power to record high-definition raw video, it is assumed that all video sources have been compressed by either MPEG-4 or H.264, and that all frame deleted video will be re-compressed using H.264 or a similar codec, where the reencoding is set to match the GOP structure of the source video.

In addition, it is assumed that all videos that are passed to the detector are of sufficient length to make a classification. Without multiple full GOPs, the presence of a deletion fingerprint is negligible. Lastly, we make the assumption that if indeed frames have been removed from a video, they have not been removed from the end of the video. The detection features are dependent on differences between the structure of the prediction error sequences in natural videos versus videos with frame deletion. When frames are removed from the end of the video sequence, this difference is not observable.

A user of our proposed system will not need physical access to a specific device to analyze a video captured by the device. The system should accept videos of an arbitrary length, and will not require metadata unrelated to video playback to be intact. It will work with videos of any resolution, frame rate, or GOP structure. Also, as our approach will be data driven, it is imperative that a user have access to a sufficient database of videos with known labels.

1.1 Video Frame Deletion Detection

Detecting frame deletion is a binary classification problem. Given a Video V, there are two possible classes:

$$\begin{aligned} &C_0 : \text{The video is genuine, and has not had frames removed from it.} \\ &C_1 : \text{The video is altered, and has had frames removed from it.} \end{aligned} \tag{1.1}$$

Note that in this case, *genuine* refers to the fact that the video has not undergone any frame deletion. A video may have underwent other post processing operations such as color correction and re-sizing but not have had any frames removed. In this case, the video would be said to be genuine. From this point forward, any mention of a genuine video simply refers to a video that has not had frames removed from it.

In general, it is difficult to classify whether or not a video has had frames removed based on the entirety of a video directly. Thus, the problem must be reworked. As shown above, a feature extraction system will be used to produce the P-frame prediction error sequence $e(n)$, and a feature vector $\boldsymbol{x}$. The feature vector ideally contains information about the prediction error sequence that can perfectly separate the two classes. As such, the classification problem is as follows. Given a feature vector $\boldsymbol{x}'$, it belongs to one of two classes:

$$\begin{aligned} &C_0 : \boldsymbol{x}' \text{resulted from a genuine video that has not had frames removed from it.} \\ &C_1 : \boldsymbol{x}' \text{resulted from an altered video which has had frames removed from it.} \end{aligned} \tag{1.2}$$

In the following chapter, we will propose both a new method for extracting $e(n)$, and additional augmentations to $\boldsymbol{x}$ that allow for improved separation of data and increased robustness of the overall system.

Chapter 2: Proposed Approach

2.1 Prediction Error Sequence Extraction

In previous work on frame deletion detection in MPEG-2, the prediction error sequence was extracted directly from the video decoder using the DCT coefficients of the prediction error residuals located in the compressed video file. The prediction error was averaged over all macroblocks in a frame. This prediction error was then stored as a sequence. Due to the nature of the correlation between P-frame prediction errors across a single GOP, any prediction made across GOP boundaries would result in increased prediction error [1]. Wang and Farid showed that for fixed GOP video, the increase in average prediction error is periodic with respect to the number of frames deleted from the video. Stamm's work expands the idea of the prediction error trace by introducing the formulation of the problem as detecting the presence of a fingerprint signal $s(n)$. As H.264 uses variable GOP structures we will only be concerned with the model defined for variable GOP video. Stamm et al. defines the model of $s(n)$ as

$$s(n) = \beta \mathbb{1} \left(\Theta(n) = 0 \right). \tag{2.1}$$

where $\beta > 0$ is a constant and $\Theta(n)$ is a random variable distributed over the set $\{0, 1\}$ [2]. This model corresponds to modeling the fingerprint signal as randomly occurring sequence of discrete impulses with a magnitude of β. From this model they pose the detection of frame deletion as distinguishing between two hypotheses:

$$\begin{aligned} &H_0 : e(n) = e_1(n). \\ &H_1 : e(n) = e_2(n) = e_1(n) + s(n)e_1(n). \end{aligned} \tag{2.2}$$

Thus, detection of frame deletion is detection of the presence of the modulated fingerprint signal $s(n)e_1(n)$. Given an unknown video, Stamm et al. first makes an approximation of the unaltered

P-frame prediction error sequence. To do this they use a median filter with a filter width of 3.

$$\hat{e}(n) = \text{median}\{e(n-1), e(n), e(n+1)\}. \tag{2.3}$$

Thus, the relationship between the estimate and $e_1(n)$ is

$$e_1(n) = \hat{e}(n) + \epsilon(n). \tag{2.4}$$

where $\epsilon(n)$ is a zero mean random variable representing estimation error.

Using the estimate of the unaltered P-frame prediction error sequence, Stamm et al. calculates $\hat{s}(n)$, which is an estimate of the fingerprint signal modulated by the prediction error sequence as defined by

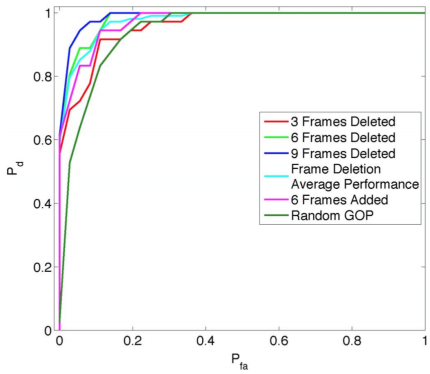
$$\hat{s}(n) = \max(e(n) - \hat{e}(n), 0). \tag{2.5}$$

The estimate of the fingerprint signal is floored at 0, as the model of the $s(n)$ dictates that it must be greater than or equal to 0. This estimate of the fingerprint signal can be used to build a detector. The decision function found by Stamm et al. for variable GOP video is

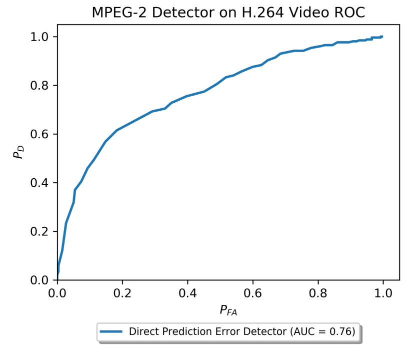
$$\delta_{var} = \begin{cases} H_0 & \text{if } \frac{1}{N}\sum_{n=1}^{N} |\hat{s}(n)| < \tau_{var} \\ H_1 & \text{if } \frac{1}{N}\sum_{n=1}^{N} |\hat{s}(n)| \geq \tau_{var} \end{cases} \tag{2.6}$$

where the decision is made on the basis of the energy in $\hat{s}$.

In MPEG-2, a P-frame is encoded by searching the previous anchor frame for the macroblock which incurs the least error [3]. This means that the average prediction error for a single P-frame is only asssociated with the previous I or P-frame. H.264 expands the capabilities of its motion compensation and estimation system by allowing prediction from multiple previous frames (and subsequent frames in the case of B-frames) [4]. If the prediction error trace is extracted via the codec for H.264, the average prediction error associated with one frame is comprised of a linear



(a) MPEG-2 Detector on MPEG-2



(b) MPEG-2 Detector on H.264

Figure 2.1: Comparison Between MPEG-2 Detection Methods used on (a) MPEG-2[a] and (b) H.264

[a]Figure reprinted with permission from Stamm et al.

combination of the average prediction error associated with motion vectors that map to the different anchor frames used in the motion estimation and compensation process. Thus, cross GOP predictions are smoothed out in such a way that it makes the fingerprint energy detector in Stamm et al.'s paper perform inadequately.

To test this, we collected 230 videos from a cell phone camera (the ASUS ZenFone 3 Laser), and generated an altered video with 15 frames removed from the beginning corresponding to each collected video. The encoding parameters were kept constant, and we fixed the GOP of the altered videos to that of the unaltered videos. In this particular case, the GOP structure was 30 frames in length, with 1 I-frame followed by 29 P-frames. We extracted the prediction error sequence directly from the codec, and measured the estimated fingerprint energy as described above.

As shown in Fig. 2.1 the perfomance of the detector using the methodology derived for MPEG-2 videos suffers a significant decrease when used on H.264 video, particularly at low false alarm rates. This is due to a limitation in the model used by Stamm et al. above in Equation 2.1. As it is possible to predict across multiple previous anchor frames in H.264, the contribution of the fingerprint signal is variable over time. This variation is also not regular, as scene content and motion determine how many cross GOP predictions are present in each P-frame. Thus we propose the updated model for the fingerprint signal as

$$s(n) = \beta(n)\mathbb{1}\left(\Theta(n) = 0\right). \tag{2.7}$$

where $\beta(n)$ is now a random variable that takes values in $\mathbb{R}_{\geq 0}$. Thus, we propose the following methodology for extracting the prediction error sequence in H.264.

2.1.1 Proposed Prediction Error Sequence Extractor for H.264

The goal of the proposed extraction algorithm is to maximize the probability that should frame deletion exist, a given measurement of the prediction error comes from a cross-GOP prediction. To this end, instead of directly measuring the prediction error from the DCT coefficients from the decoder, we decode the frame of interest and store the motion vectors associated with said frame. For each motion vector in the current P-frame, we find the x and y coordinates defining the source macroblock which provides the least error mapping from a particular previous anchor frame. Then for that previous anchor frame, we subtract the pixels in the source macroblock from the destination macroblock in the current frame. This leaves us with a prediction error residual associated with the motion vector. We then calculate the average absolute value of this residual.

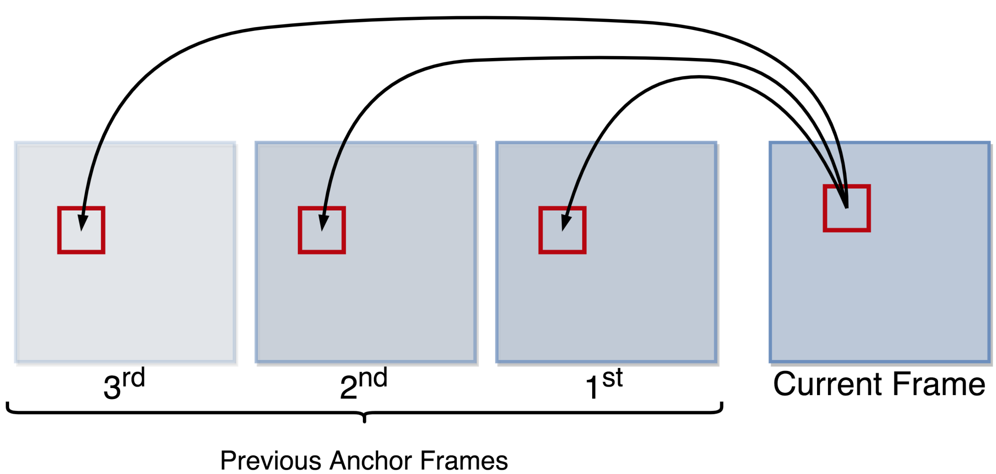


Figure 2.2: Identification of the source macroblock in 3 previous anchor frames

We repeat this process for each of D previous anchor frames. Then we store these prediction error values in a matrix $M[n]$, where n denotes the P-frame index of the current frame. Each row of the matrix corresponds to the errors associated with a single motion vector, and the columns are the errors associated with each of the previous anchor frames.

After obtaining the $M[n]$ matrix for the current frame, we create the matrix $\tilde{M}[n]$ defined like so:

$$\tilde{M}_{i,j}[n] = \mathbb{1}\left(j = \underset{l}{\operatorname{argmin}}\,(M_{i,l}[n])\right) * M_{i,j}[n] \tag{2.8}$$

Thus $\tilde{M}[n]$ is a copy of $M[n]$ where the non-zero entries in each row correspond to the minimum average error associated with the macroblock and all other elements are zero. Effectively, the column index of the non-zero entry is an estimation of which previous frame the motion vector associated with the macroblock maps to in the decoding process.

Further processing is done on $\tilde{M}[n]$ to output only a single prediction error value. First, $\tilde{M}[n]$ is reduced into a vector $P[n]$, such that:

$$P_j[n] = \frac{1}{N_j} \sum_i \tilde{M}_{i,j}[n] \tag{2.9}$$

Where N_j is the number of non-zero elements in the j^{th} column of $\tilde{M}[n]$. Then, the reported prediction error for the current frame $e * [n]$ is calculated as

$$e^*[n] = \max_j P_j[n] \tag{2.10}$$

This entire process is repeated for every P frame in the video. This method of error extraction estimates which previous anchor frame contributes the maximum error per macroblock to the overall prediction error residual obtained by the codec for a given P frame. Since prediction across GOP boundaries results in spikes in the prediction error, the anchor frame that contributes the most error is most likely to be from a different original GOP. In this manner, we obtain a trace that is resilient to advances made in the motion compensation and estimation process in modern codecs as well as robust to variable frame rates and dynamic GOP structures.

$$M[n] = \begin{bmatrix} 30.4 & 20.5 & 40.2 \\ 16.3 & 22.1 & 30.4 \\ 25.5 & 23.4 & 19.8 \\ \vdots & \vdots & \vdots \end{bmatrix}$$

$$\tilde{M}[n] = \begin{bmatrix} 0.00 & \mathbf{20.5} & 0.00 \\ \mathbf{16.3} & 0.00 & 0.00 \\ 0.00 & 0.00 & \mathbf{19.8} \\ \vdots & \vdots & \vdots \end{bmatrix}$$

$$P[n] = \begin{bmatrix} P_1[n] & P_2[n] & P_3[n] \end{bmatrix}$$

Figure 2.3: Methodology for forming $P[n]$

2.2 Proposed Detection Algorithm

In addition to the new methods for prediction error extraction, we propose an expanded detection algorithm to better capture the statistical differences between videos. In fact, depending on scene content, video capture settings, and the amount of motion captured in a single recording, the prediction error sequence and fingerprint signal exhibit different structural behavior. This is true even for videos captured from a single camera model. Figure 2.4 shows this clearly. The two videos were captured from an LG Nexus 5X using the high quality 1080p capture mode. Both videos were shot using similar scene content, but the amount of motion in each video is different. The first video was shot with hight motion, while the second video was comparatively low motion. The top row shows the different prediction error sequences, while the bottom row shows the different estimated fingerprint signals.

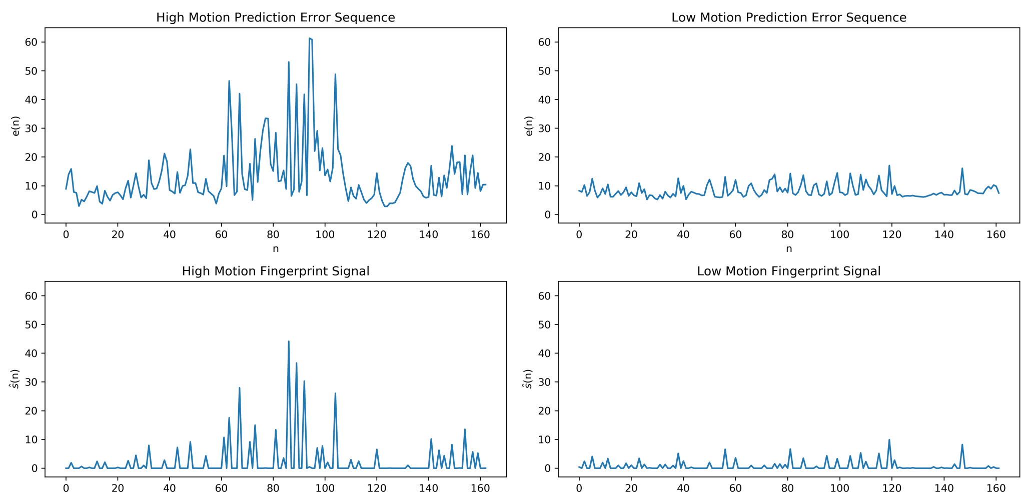


Figure 2.4: *Top Left* - The extracted prediction error sequence for a high motion video. *Top Right* - The extracted prediction error sequence for a low motion video. *Bottom Left* - Estimated fingerprint signal for a high motion video. *Bottom Right* - Estimated fingerprint signal for a low motion video.

Notice the large discrepancy in magnitude between both types of signals depending on the amount of motion in the video. The original detection criteria defined by Stamm et al. in Equation 2.6 is based on the energy of the estimated fingerprint signal. This will lead to undesirable misclassifications when only using signal energy as the detection feature. Thus, we need a set of new features that can help account for this difference in fingerprint signal energy between videos.

Under the old model for the fingerprint signal, β was a constant, meaning the fingerprint signal was thought of as a randomly occurring sequence of discrete impulses with a magnitude of β. With the new model defined in Equation 2.7, $\beta(n)$ is a random variable that takes nonnegative real values. The effect of $\beta(n)$ can be seen in Fig. 2.5. The sample low motion video was reencoded with the first 15 frames removed. This accounts for half of a GOP. As the GOP structure of the video is fixed, it is expected that the fingerprint signal will be periodic **Stamm** The estimated fingerprint signal of the sample video with frame deletion shows some amount of periodicity but the amplitude of the signal varies with time. Modeling this variation of $\beta(n)$ for a given video can help aid in the detection of frame deletion.

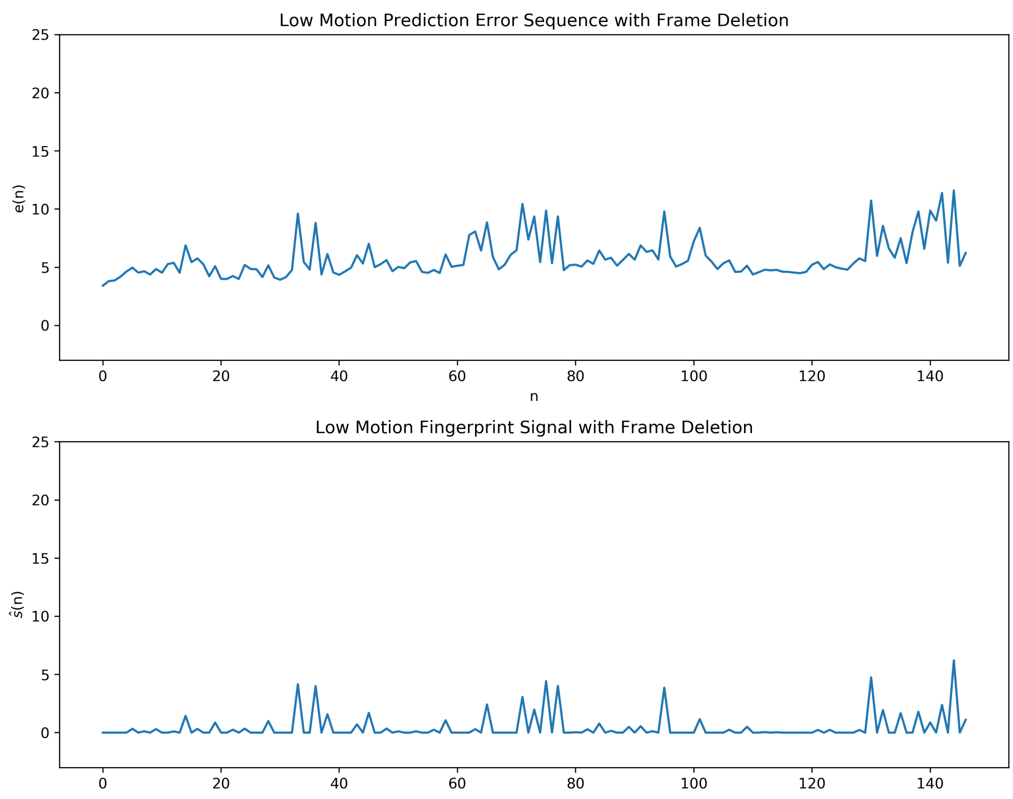


Figure 2.5: *Top* - The extracted prediction error sequence for a low motion video with frame deletion. *Bottom* - The Estimated fingerprint signal for a low motion video with frame deletion.

Over several seconds of video both the prediction error sequence and the fingerprint signal are wide sense stationary. Due to this, we propose modeling both the fingerprint signal and prediction error sequence as autoregressive (AR) processes. The model parameters capture some of the statistical information about $\beta(n)$, and thus are added to a feature vector along with the fingerprint energy. In order to capture the degree to which the model fits a given sequence, the error variance of each AR model is also included. In addition, some basic statistical features are included to scale the overall decision surface. We propose including the mean and variance of both the prediction error sequence and fingerprint signal to the feature vector as well.

For a given video V, the feature vector used for classification $\boldsymbol{x}_V$ is structured as

$$\boldsymbol{x}_V = \begin{bmatrix} [c]\frac{1}{N}\sum_{n=1}^{N}|\hat{s}[n]| \\ \mu_{\hat{s}} \\ \sigma^2_{\hat{s}[n]} \\ \mu_{e^*[n]} \\ \sigma^2_{e^*[n]} \\ \boldsymbol{a}_1 \\ \boldsymbol{a}_2 \end{bmatrix} \tag{2.11}$$

Where $\hat{s}[n]$ is the estimated fingerprint sequence of $e^*[n]$ obtained by using Equation 2.5 above, but substituting $e^*[n]$ for $e[n]$, μ is the sample mean, σ^2 is the sample variance, $\boldsymbol{a}_1$ are the Q^{th} order AR model parameters for $e^*[n]$, and $\boldsymbol{a}_2$ are the Q^{th} order AR model parameters for $\hat{s}[n]$.

Note that after creating a feature vector for each video, the feature vector is quite large. It is inadvisable to create a probabilistic model of the feature vector for classification. Instead, we propose using a discriminative function to map an incoming feature vector directly to the set of natural videos or the set of videos altered by frame deletion. As such, we propose using a Support Vector Machine (SVM) classifier with a Radial Basis Kernel function for classification [5].

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