# A DISTORTION CONTROL ALGORITHM FOR PIXEL-DOMAIN WYNER-ZIV VIDEO CODING

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**ABSTRACT**

In contrast to conventional video coding, Wyner-Ziv video coders perform simple intra-frame encoding and complex inter-frame decoding. This feature makes this type of coding suitable for applications that require low-complexity encoders. In this paper, we present a model of the coding distortion introduced by pixel-domain Wyner-Ziv video coders. Our distortion model can be used to determine the value of coding parameters under certain coding constraints. Specifically, we show how our model can be used to select the quantization step size of each video frame so that a target distortion can approximately be met. Experimental results show that, even though the accuracy of the distortion predictions is limited by the restricted computational capacity of Wyner-Ziv encoders, the described distortion constraints can be approximately fulfilled by using our model.

***Index Terms—*** Wyner-Ziv video coding, distributed video coding

## 1. INTRODUCTION

In conventional video coders, motion estimation is performed at the encoder in order to exploit the redundancy in the video frames. Due to the large complexity of motion estimation algorithms, motion-compensated encoders are much more complicated than their correspondent decoders. Some video applications, however, require low-complexity encoders. This feature can be achieved by using Wyner-Ziv video (WZV) coders, which perform simple intra-frame encoding and complex inter-frame decoding [1–3].

Most video coding applications impose rate and distortions constraints. Video coding standards provide coding modes (e.g., SKIP, INTRA, INTER) and parameters (e.g., QP) so that encoders can fulfill rate/distortion constraints and improve their coding efficiency. To choose coding modes and parameter values in a proper way, rate-distortion models can be used. Obtaining good rate-distortion models is more difficult in WZV coding than in conventional video coding because WZV encoders cannot accurately measure the statistics of input video, and hence, cannot precisely predict the distortion or the rate of the frames. For instance, a WZV encoder cannot know the distortion of a frame since the frame that is used to conditionally decode it is only available at the decoder. Despite this limitation, the use of rate/distortion models can help WZV coders to fulfill distortion and/or rate constraints and to increase their coding efficiency.

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Video coders can control the distortion or the rate of the encoded video by adaptively setting the quantization step size $\Delta$ of each coding unit. However, most PDWZ video coders do not provide any algorithm to properly set parameter $\Delta$ so that distortion or rate constraints can be fulfilled [1–7]. Instead, these coders choose an arbitrary value of $\Delta$ and use it in all the frames of the video sequence to be encoded. This simple strategy does not allow PDWZ video coders to fulfill distortion or rate constraints, and hence, it can considerably limit the number of applications where these coders can be used.

In this paper, we present a distortion model for pixel-domain Wyner-Ziv (PDWZ) video coders. Our model provides the coding distortion of a frame $\mathbf{X}$ as a function of the quantization step value ($\Delta$) and a parameter $\alpha$ that depends on the accuracy of the frame that is used to conditionally decode $\mathbf{X}$ at the decoder. The model can be used by PDWZ coders to adaptively set $\Delta$ in distortion-constrained encodings. Thus, once the parameter $\alpha$ of a frame has been estimated, a PDWZ encoder can estimate the value of $\Delta$ that provides the distortion that is closest to the target distortion. In this way, a PDWZ coder can approximately fulfill distortion constraints.

## 2. PIXEL-DOMAIN WYNER-ZIV VIDEO CODING

In this section, we review the basics of PDWZ video coding. Figure 1 shows the block diagram of a PDWZ video coder. In PDWZ coders, the frames are organized into key frames (K-frames) and Wyner-Ziv frames (WZ-frames). The K-frames are coded using a conventional intra-frame coder. The WZ-frames are coded using the Wyner-Ziv paradigm, *i.e.*, they are intra-frame encoded but are conditionally decoded using side information (SI). For each WZ-frame $\mathbf{X}$, an approximation $\mathbf{Y}$ is obtained at the decoder by extrapolating or interpolating previously decoded K-frames. The frame $\mathbf{Y}$ constitutes part of the SI used in the decoding of $\mathbf{X}$ [1–3].

Let $M$ be the number of bits used to represent the amplitude values of frame pixels. In each WZ-frame, the PDWZ encoder is allowed to transmit a maximum number $L$ of the $M$ bitplanes (BPs). To encode a WZ-frame $\mathbf{X}$, first, the $m$ ($m \leq L$) most significant BPs $\{\mathbf{X}_1, \ldots, \mathbf{X}_m\}$ are extracted. Parameter $m$ can be a fixed value [2–6, 8] or can be adaptively determined by an adequate algorithm depending on the coding constraints (e.g. see Section 4). Then, each BP $\mathbf{X}_p$ ($1 \leq p \leq m$) is independently encoded using a Slepian-Wolf (SW) coder [2–6, 8]. The encoding, transmission and decoding of BPs is done in order of significance (the most significant BPs are transmitted and decoded first). The SW coder is implemented using a channel coder that yields parity bits of $\mathbf{X}_p$, which are transmitted. On the decoder side, the SW decoder is a channel decoder that obtains each BP $\mathbf{X}_p$ from the transmitted parity bits, the corresponding BP $\mathbf{Y}_p$ extracted from $\mathbf{Y}$, and the previously decoded BPs $\{\mathbf{X}_1, \ldots, \mathbf{X}_{p-1}\}$[1]. Once the SW decoder has decoded the $m$ most significant BPs of $\mathbf{X}$, the decoder obtains a reconstruction $\hat{\mathbf{X}}$ of $\mathbf{X}$ by using $\{\mathbf{X}_1, \ldots, \mathbf{X}_m\}$ and $\mathbf{Y}$ [3]. To determine the number of parity bits of a BP to be transmitted, a rate-adaptive channel coder together with a feedback channel is used [1].

Note that $\{\mathbf{X}_1, \ldots, \mathbf{X}_p\}$ constitutes a quantized version of $\mathbf{X}$ using a uniform quantizer of $p$ bits with step size $\Delta = 2^{M-p} - 1$. The larger $p$, the smaller $\Delta$, and, therefore, the larger the rate $R$ and the lower the distortion of the decoded video. Thus, if the $m$ most significant BPs are encoded by the SW coder, $m+1$ different decodable bitstreams $\{\mathrm{BS}_0, \ldots, \mathrm{BS}_m\}$ can be generated for each WZ-frame $\mathbf{X}$, where $\mathrm{BS}_p$ contains parity bits of the $n$ most significant BPs. When $p = 0$, no BP is transmitted ($\mathrm{BS}_0$ does not contain any parity bits) and each decoded frame $\mathbf{X}$ is equal to $\mathbf{Y}$. Consequently, with the *scalable* coder shown in Figure 1, $m+1$ different rate-distortion points are possible. In *non-scalable* PDWZ video coders [1], each WZ-frame is quantized using a uniform quantizer and the SW coder directly encodes the quantization indexes. In these coders, once the quantizer step size $\Delta$ of $\mathbf{X}$ has been set, only *one* rate-distortion point is possible.

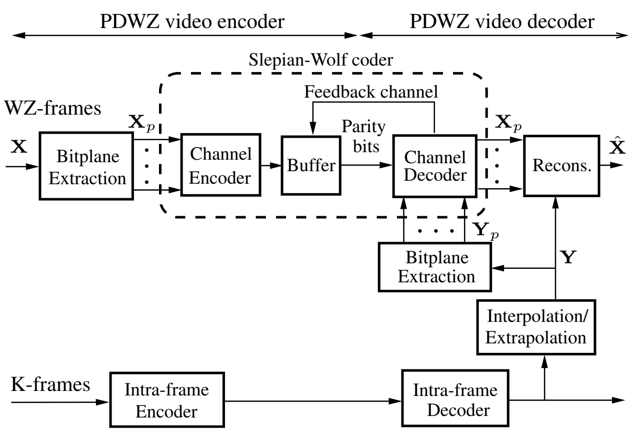


**Fig. 1**. Block diagram of a PDWZ video coder.

## 3. THE DISTORTION MODEL

In this section, we analyze the distortion of a PDWZ video coder. Let $X$ and $Y$ be continuous and correlated random variables representing the signal to be encoded and the SI, respectively. Let $Z$ be the *correlation noise*, *i.e.*, $Y = Z + X$ with $Z$ and $X$ being independent. Let $x$, $y$ and $z$ be outcomes of $X$, $Y$ and $Z$ respectively. We assume that $X$ distributed in $[x_{\min}, x_{\max}]$ and that a uniform quantizer with $N$ decision intervals $[x_n, x_{n+1}]$ ($n = 0, \ldots, N-1$) of length $\Delta$ is used ($\Delta = (x_{\max} - x_{\min})/N$). Moreover, we assume $Z$ follows a Laplacian distribution with a probability density function (pdf) $f_Z(z) = \alpha/2 \exp(-\alpha|z|)$, where $\alpha = \sqrt{2}/\sigma$ and $\sigma$ is the standard deviation of $Z$. As in [3,7], the reconstruction $\hat{x}$ of $x$ is obtained through

$$\hat{x}(y, x_n, x_{n+1}) = \begin{cases} x_n & \text{if } y < x_n \\ y & \text{if } x_n \leq y \leq x_{n+1} \\ x_{n+1} & \text{if } y > x_{n+1} \end{cases} \tag{1}$$

[1]In practical PDWZ video coding, SW decoders are allowed to introduce a certain small number of errors

where $[x_n, x_{n+1}]$ is the quantization interval that $x$ belongs to. This reconstruction function provides worse estimates than the minimum-mean-squared-error (MMSE) estimate, but this loss in performance is small except when $\sigma^2$ is large or when $\Delta$ is small. However, function (1) requires less computations than the MMSE estimate.

The quadratic distortion introduced in the encoding of a certain value $x$ of $X$ using $Y$ as side information at the decoder is

$$D_{\mathrm{WZ}}(x) = \int_{-\infty}^{\infty} (x - \hat{x})^2 \, f_{Y|X}(y|x) \, dy \tag{2}$$

where $f_{Y|X}(y|x)$ is the conditional pdf of $Y$ given $X$. As $Z$ is an additive noise, then $f_{Y|X}(y|x) = f_Z(y - x)$, and as $Z$ follows a Laplacian distribution, then

$$f_{Y|X}(y|x) = \frac{\alpha}{2} \, e^{-\alpha|x-y|}. \tag{3}$$

By substituting (3) and (1) into (2) and solving the integral, we obtain

$$\begin{aligned} D_{\mathrm{WZ}}(x) \quad &= \quad \frac{2}{\alpha^2} + e^{-\alpha(x - x_n)} \left( \frac{1}{\alpha}(x_n - x) - \frac{1}{\alpha^2} \right) \\ &+ \quad e^{-\alpha(x_{n+1} - x)} \left( \frac{1}{\alpha}(x - x_{n+1}) - \frac{1}{\alpha^2} \right) \end{aligned} \tag{4}$$

where $[x_n, x_{n+1}]$ is the quantization interval that $x$ belongs to.

From (4), we can compute the average quadratic distortion $D_{\mathrm{WZ}}$ introduced in the encoding of $X$ through

$$D_{\mathrm{WZ}} = \int_{-\infty}^{\infty} D_{\mathrm{WZ}}(x) \, f_X(x) \, dx \tag{5}$$

where $f_X(x)$ is the pdf of $X$. By taking into account that the quantizer has $N$ intervals, we obtain

$$D_{\mathrm{WZ}} = \sum_{n=0}^{N-1} \int_{x_n}^{x_{n+1}} D_{\mathrm{WZ}}(x) \, f_X(x) \, dx. \tag{6}$$

As in the case of images, the pixels values do not follow any statistical model, we assume $X$ is uniformly distributed in $[x_{\min}, x_{\max}]$, and hence

$$D_{\mathrm{WZ}} = \frac{1}{x_{\max} - x_{\min}} \sum_{n=0}^{N-1} \int_{x_n}^{x_{n+1}} D_{\mathrm{WZ}}(x) \, dx \tag{7}$$

and as the quantizer is uniform, the integral in (7) has the same value in all the intervales and hence

$$D_{\mathrm{WZ}} = \frac{N}{x_{\max} - x_{\min}} \int_{x_n}^{x_{n+1}} D_{\mathrm{WZ}}(x) \, dx. \tag{8}$$

Finally, by substituting (4) into (8), and solving the integral in (8) we obtain

$$D_{\mathrm{WZ}} = \frac{2}{\alpha^2} \left( 1 + e^{-\alpha\Delta} \right) + \frac{4}{\alpha^3 \Delta} \left( e^{-\alpha\Delta} - 1 \right). \tag{9}$$

When using (9) to obtain the distortion in DV coders, the limitations of the assumed hypotheses must be taken into account. First, the pixel values of frames are discrete-amplitude values rather than continuous-amplitude values. Second, pixel values are clipped to an interval; however, to derive our model, we have assumed that the SI pixel values can have any real value. Third, the pixel value distribution in practice can be far from the uniform distribution assumed to derive (9). A distribution different to the uniform could be used if the pixel amplitude distribution is measured. Notice, however, that this would increase the complexity of the encoder. Finally, the correlation noise distribution is, in general, more peaked and has longer tails than the assumed Laplacian distribution.

## 4. THE FRAME-ADAPTIVE $\Delta$-SELECTION ALGORITHM

In a PDWZ video coder, a quantization parameter has to be provided for both the K- and the WZ-frames. For the K-frames, a transform-based intra-frame coder is usually used, and the quantization step size is determined by the QP parameter. For the WZ-frames, $L+1$ different quantization step sizes $\Delta$ are possible. The quantization parameter has to be adaptively set in order to fulfill rate, distortion or delay constraints and to improve coding efficiency. However, in most PDWZ algorithms so far, all the K- and WZ-frames are encoded using the same QP and $\Delta$ values, respectively [1, 2, 4, 5]. To select the proper QP for a given $\Delta$, some of these algorithms encode the sequence with several QP values and then select the one that provides the lowest quality fluctuations. In the following, we call this off-line strategy the *constant $\Delta$ algorithm*.

In this section, we present an algorithm to adaptively select the quantization parameter for both K- and WZ-frames when a target distortion must be met. This is important since the use of our algorithm can allow a PDWZ video coder to fulfill a distortion constraint at the expense of a slight increase in the complexity of its encoder. Our algorithm can be used in both non-scalable and scalable PDWZ video coders. In non-scalable PDWZ video coders [1], our algorithm provides the quantizer $\Delta$ of each WZ-frame. In scalable PDWZ video coders, the $\Delta$ provided by our algorithm determines the number $m$ of BPs to transmit.

To determine the QP parameter of K-frames, we compute, after encoding a K-frame, its distortion $D_{\rm K}$ and compare it to the target distortion $D_t$. If $|D_{\rm K} - D_t|$ is below a threshold $T$, then the same QP value is used in the next K-frame. Otherwise, we change the QP value for the next K-frame in such a way that if $D_{\rm K} > D_t$, then QP = QP - 1 and if $D_{\rm K} < D_t$, then QP = QP + 1. To encode the first K-frame, we use a default QP$_0$ value. To select the proper $\Delta$ value for a WZ-frame $\mathbf{X}$, we use the distortion model of Section 3. According to (9), the coding distortion $D_{\rm WZ}$ depends on $\alpha$ and $\Delta$. However, $\alpha$ cannot be computed since $\mathbf{Y}$ is not available at the encoder, and therefore, an estimate $\hat{\alpha}$ of $\alpha$ must be first computed. Several methods to estimate $\alpha$ have been proposed in the literature [5, 8]. Then, the distortion of $\mathbf{X}$ for $\Delta_v = 2^{M-v}-1$, denoted $D_{\rm WZ}^{(v)}$, is computed for $v = 0, \ldots, L$. Finally, the optimum $\Delta$ value for $\mathbf{X}$ is chosen. Therefore, the following steps are performed by our algorithm:

1. Compute $\hat{\alpha}$ and set $D_{\rm WZ}^{(0)}$ to $2/\hat{\alpha}^2$.
2. For $v = 1, \ldots, L$, compute $D_{\rm WZ}^{(v)}$ using (9) with $\alpha = \hat{\alpha}$ and $\Delta = \Delta_v$.
3. Set $m$ to the $v$ value such that $|D_{\rm WZ}^{(v)} - D_t|$ is minimum.
4. Set the optimum $\Delta$ to $2^{M-m}-1$

In practice, the $\hat{\alpha}$ estimates can exhibit a bias. In this case, the criterion for selecting the optimum $m$ value (step 3), can be modified in order to reduce the effect of the bias. This is illustrated in Section 5.

## 5. EXPERIMENTAL RESULTS

We experimentally tested the validity of the distortion model presented in Section 3 and the $\Delta$-selection algorithm presented in Section 4. To obtain experimental results, we implemented a PDWZ video coder with the structure shown in Figure 1. In this coder, the odd frames are encoded as K-frames and the even frames are encoded as WZ-frames [1–6, 8]. As in [4, 5], K-frames are encoded as intra-frames using a standard intra H.263+ coder. The SW coder uses a rate-compatible turbo coder with a puncturing period of 32. The turbocoder is composed of two identical constituent convolutional encoders of rate 1/2 with generator polynomials $(1, 33/23)$ in octal form. The decoder uses the interpolation tools described in [2] to generate the SI. Reconstruction is done using reconstruction function (1). The test sequences have a QCIF resolution ($176 \times 144$ pixels/frame, 30 frames/second) and for the encoding only the luminance component was considered. The coding efficiency of this algorithm is similar to the one in [6] when they operate with the same quantization parameter values.

To test the validity of the distortion model of Section 3, we encoded the first 299 frames of the *Akiyo*, *Foreman*, and *Mobile* sequences using our PDWZ video coder. In each sequence, the H.263+ quantization parameter QP was set so that the mean PSNR of K-frames was close to 33 dB. For each sequence, the four most significant BPs of the WZ-frames were encoded ($L = 4$). Then, five bitstreams $\{{\rm BS}_0, \ldots, {\rm BS}_4\}$ were generated and decoded. Finally, the PSNR values (in dB) of the WZ-frames corresponding to each bitstream ${\rm BS}_m$ were computed and averaged. The resulting mean PSNR values for each sequence and $m$ are shown in Figure 2.

For each video sequence and $m$ value, the theoretical mean PSNR value was also computed. To do this, in each WZ-frame, the theoretical distortion of each bitstream ${\rm BS}_m$ was computed by substituting $\Delta = 2^{8-m}-1$ and $\alpha = \sqrt{2/{\rm MSE}}$ in (9), where MSE is the mean squared error between $\mathbf{X}$ and its interpolated frame $\mathbf{Y}$. The theoretical distortion of ${\rm BS}_0$ was set to its MSE value. Finally, the PSNR (in dB) of the WZ-frames were computed and averaged for each $m$, and the results are shown in Figure 2. Figure 2 shows that both the theoretical and the experimental curves follow the same main trends. Note, however, that the theoretical mean PSNR is lower than the experimental mean PSNR. The main reason for this discrepancy is that, as we have already mentioned, the correlation noise distribution has larger tails than the Laplacian distribution, which provides larger distortion reductions than those predicted theoretically.

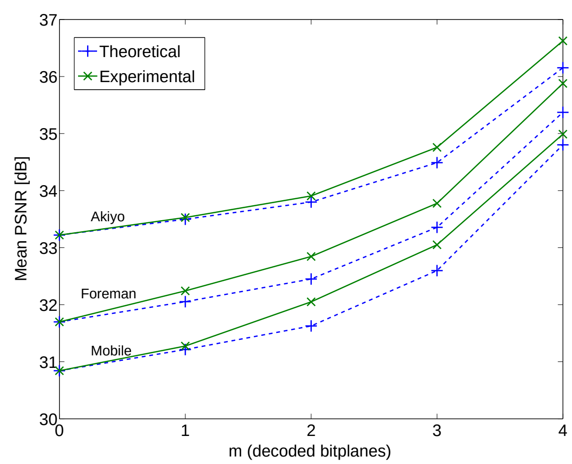


**Fig. 2**. Theoretical and experimental mean PSNR of the WZ-frames

To test the efficiency of our $\Delta$-selection algorithm, we encoded 299 frames of several QCIF sequences using the algorithm of Section 4 with two different target PSNR (PSNR$_{\rm t}$) values: 30 dB and 36 dB. For the K-frames, QP$_0$ was set to 10 in all the encodings, and $T$ was set to 0.25. For each WZ-frame $\mathbf{X}$, $\hat{\alpha}$ was set to $\sqrt{2/{\rm MSE}'}$ where ${\rm MSE}'$ is the mean square error between $\mathbf{X}$ and the average of its two closest decoded K-frames. The computation of $\hat{\alpha}$ increases the complexity of the PDWZ encoder, mainly because K-frames have to be decoded also at the encoder side. Other $\alpha$ estimates that require less encoder computations can be used [5, 8]. As shown above, in each WZ-frame, our model predicts a distortion that is generally larger than the real distortion. This bias is reinforced by the fact that $\hat{\alpha}$ is an underestimate of $\alpha$ in most frames. Because of this bias, the algorithm of Section 4 tends to provide WZ-frames with a distortion that is lower than $D_t$. To reduce the bias, in contrast to what is proposed in the algorithm of Section 4, we set $m$ to the maximum $v$ such that $D_{\mathrm{WZ}}^{(v)} \geq D_t$. When $D_{\mathrm{WZ}}^{(0)} \leq D_t$, then $m$ was set to 0 ($\Delta = 255$).

Figure 3 shows the PSNR of each decoded frame of the sequence Carphone when $\mathrm{PSNR_t}$= 36 dB. It also shows the PSNR of each interpolated frame $\mathbf{Y}$. Note that, despite the large variations in the PSNR of the interpolated frames, our algorithm selected the $\Delta$ value of each WZ-frame so that the PSNR was close to $\mathrm{PSNR_t}$. Table 1 shows the mean PSNR (in dB) of K-frames and WZ-frames obtained after encoding several QCIF video sequences using our $\Delta$-selection algorithm with two $\mathrm{PSNR_t}$ values (30 dB and 36 db). Table 1 also shows the mean rate $R$ (in kbps) of the WZ-frames. As in [1–3], the mean rate values were computed considering that the WZ-frame rate was 15 frames/s. Note that the mean PSNR values of K-frames are closer to $\mathrm{PSNR_t}$ than the mean PSNR of WZ-frames. There are two main reasons for this. First, there are 31 different values of QP for K-frames but only five different $\Delta$ values for WZ-frames, and hence, quality can be set in a more precise way in K-frames than in WZ-frames. Second, the encoder can *exactly* compute the distortion introduced in the encoding of each K-frame and set QP accordingly. The distortion of WZ-frames, however, can only be estimated.

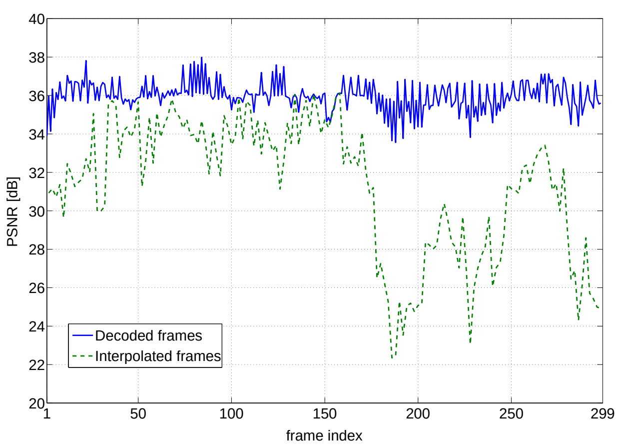


**Fig. 3**. PSNR of the decoded frames and the interpolated frames of Carphone using our $\Delta$-selection algorithm with $\mathrm{PSNR_t}$=36 dB.

| Video sequence | $\mathrm{PSNR_t}$ = 30 dB | | | $\mathrm{PSNR_t}$ = 36 dB | | |
|---|---|---|---|---|---|---|
| | K-frames | WZ-frames | | K-frames | WZ-frames | |
| | PSNR | PSNR | $R$ | PSNR | PSNR | $R$ |
| Carphone | 30.1 | 30.5 | 140 | 36.0 | 36.0 | 419 |
| Foreman | 30.1 | 30.8 | 129 | 35.9 | 36.5 | 347 |
| Mobile | 30.1 | 30.0 | 113 | 35.8 | 35.8 | 440 |
| Silent | 30.0 | 30.2 | 119 | 36.0 | 36.6 | 292 |

**Table 1**. The mean PSNR (in dB) of K-frames and WZ-frames, and the mean rate (in kbps) of WZ-frames obtained using our $\Delta$-selection algorithm with two target PSNR values (30 dB and 36 dB).

We compared the constant $\Delta$ algorithm and our algorithm by encoding several sequences with our PDWZ video coder using both strategies. Our algorithm provided PSNR values closer to the $\mathrm{PSNR_t}$ than the constant $\Delta$ algorithm in most encodings. For instance, in the encoding of Carphone with $\mathrm{PSNR_t}$=36 dB, the average absolute difference between the PSNR of each frame and $\mathrm{PSNR_t}$ was 0.91 dB in the constant $\Delta$ algorithm but 0.53 dB in our algorithm. Therefore, despite the errors in estimating $\alpha$, our algorithm better approaches the target PSNR without encoding the video sequence several times (as in the constant $\Delta$ algorithm).

## 6. CONCLUSIONS AND FUTURE WORK

We have presented a model for the distortion introduced in pixel-domain Wyner-Ziv video coders. The model can be used to help coders of this type to fulfill coding constraints and improve their efficiency. As an example of the application of our model, we have proposed an algorithm to select the quantization parameter of each frame in distortion-constrained encodings. Despite the restricted capacity of Wyner-Ziv video encoders to accurately estimate the model parameter, experimental results show that our model allows us to approach the target distortion. In our algorithm, the rate of WZ-frames was freely chosen to fulfill distortion constraints. Since rate and delay constraints are also important in many applications, we are currently extending our approach to include them as well.

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