ANALYSIS OF ERROR-RESILIENT VIDEO TRANSMISSION BASED ON SYSTEMATIC SOURCE-CHANNEL CODING

(Invited Paper)

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***Abstract*— This paper discusses the modeling and analysis of a systematic lossy source channel coding system for error-resilient video transmission. The systematic portion of the transmission consists of a video bitstream transmitted without channel coding over an error-prone channel. Error-resilience is achieved by transmitting a supplementary bitstream generated by Wyner-Ziv encoding of the video signal. The scheme is attractive because it provides gracefully decreasing video quality over a range of symbol error rates, when compared with conventional FEC. We propose a model for the end-to-end video distortion delivered by this system. The model considers the encoder's rate-distortion trade-off, quantization mismatch from Wyner-Ziv coding, previous frame error concealment and error propagation. The model predictions agree closely with experimental results and thereby suggest an optimization algorithm to find the best rate-distortion trade-off for systematic lossy forward error protection of video waveforms.**

I. INTRODUCTION

In typical video transmission systems, a video signal encoded using MPEG1/2 or H26x is transmitted to one or more receivers. To correct transmission errors, the source bitstream is generally protected using some form of forward error correction (FEC). The FEC scheme, along with decoder-based error concealment ensures that the video quality is acceptable for the given channel conditions. However, the video quality degrades rapidly when the channel error rate exceeds the error correction capability of the FEC codes, leading to the undesirable "cliff" effect. In our recent work on distributed video coding [1]–[3], we proposed the systematic lossy forward error protection scheme, which uses Wyner-Ziv coding instead of conventional FEC. In this paper, we develop a model for the end-to-end distortion of this system and the use this model for analysis and optimization of the forward error protection system.

Wyner-Ziv coding refers to lossy compression with side information at the decoder. Achievable rates for this setting were derived in the mid-1970s by Wyner and Ziv [4]–[6]. It was proved that the minimum encoding rate for a source sequence X, at a given distortion, when the side information Y is only known to the decoder, is greater than or equal to the rate obtainable when the side information is also available at the encoder. It has been shown in [7] that, for mean-squared error distortion, the rate loss associated with ignoring the side information at the encoder is bounded from above, and is actually zero for jointly Gaussian X and Y.

The Wyner-Ziv problem is closely related to the problem of systematic lossy source-channel coding [8]. In this configuration, an analog source X is transmitted over an analog Channel A without coding. A second encoded version of X is sent over a digital Channel D as enhancement information. The noisy version Y of the original serves as side information to decode the output of Channel D and produce the enhanced version Y^*. The term "systematic coding" has been introduced as an extension of systematic error-correcting channel codes to refer to a partially uncoded transmission. Shamai, Verdú, and Zamir established information theoretic bounds and conditions for optimality of such a configuration in [8].

The systematic coding framework was used by Pradhan and Ramchandran [9] for enhancing the quality of images corrupted by additive white Gaussian noise, using digital side information. In our own work, we used the systematic coding paradigm for error-resilient digital video broadcasting, first using a simple pixel-domain Wyner-Ziv codec for a proof-of-principle [10], followed by an improved practical Wyner-Ziv codec [2], [3], comprised of a hybrid video codec and a Reed-Solomon Slepian-Wolf codec.

The systematic coding scheme for error resilience differs from other recently proposed schemes for distributed video coding [11]–[15]. The difference is that, in these schemes, the Wyner-Ziv codec is an integral part of the video encoding and is necessary for both source coding efficiency and resilience to channel errors. In contrast, the systematic source-channel coding scheme uses the Wyner-Ziv codec solely for error-resilience and is, in principle, independent of the video compression scheme employed for the systematic transmission.

The remainder of this paper is organized as follows. In Section II, we explain the principle of systematic lossy forward error protection (FEP). In Section III, we develop a model for the end-to-end distortion for the FEP system, focussing on the effect of quantization mismatch, error concealment, and propagation of concealment and quantization errors. In Section IV we confirm that the model closely approximates the end-to-end distortion obtained in actual experiments and suggest a method to obtain the optimal rate-distortion tradeoff for the given channel conditions.

II. SYSTEMATIC LOSSY SOURCE CHANNEL CODING OF VIDEO WAVEFORMS

The concept of systematic lossy forward error protection is illustrated in Fig. 1, using MPEG video broadcasting as an example. At the transmitter, the input video signal S is compressed independently by an MPEG video coder and a Wyner-Ziv coder. Since the MPEG video bitstream is generated without consideration of the error resilience provided by the Wyner-Ziv coder, we refer to the overall scheme as systematic source-channel coding. The video signal compressed by MPEG and transmitted over an error-prone channel constitutes the systematic portion of the transmission, which is augmented by the Wyner-Ziv bitstream. At the receiver, the MPEG bitstream is decoded and transmission errors are concealed, resulting in the decoded video S'. Even after concealment, S' contains some portions that are degraded by unacceptably large errors. These errors are corrected, up to a certain residual distortion, by the Wyner-Ziv decoder. The Wyner-Ziv code can be thought of as a second, independent description of the input video S, but with coarser quantization. Without transmission errors, the Wyner-Ziv description is then fully redundant, i.e., it can be regenerated bit-by-bit at the decoder, using the decoded video S'.

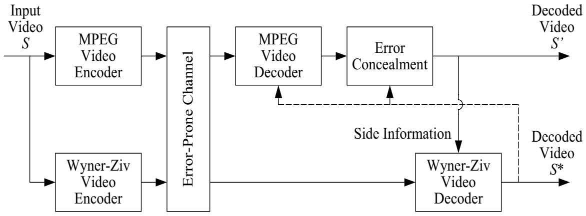

Fig. 1. Wyner-Ziv decoder uses decoded error-concealed video waveform as side information in systematic lossy source-channel setup.

When transmission errors occur, Wyner-Ziv bits must be sent to allow error-free reconstruction of the coarser second description, employing the decoded video signal S' as side information. The error correction capabilities of the Wyner-Ziv bitstream can be simultaneously used to protect the Wyner-Ziv bits against transmission errors. The coarser second description and side information S' are combined to yield an improved decoded video signal S^*. In portions where the waveform S' is not affected by transmission errors, S^* is essentially identical to S'. However, in portions of the waveform where S' is substantially degraded by transmission errors, the second coarser representation transmitted at very low bit-rate in the Wyner-Ziv bitstream limits the maximum degradation that can occur. Instead of the error-concealed decoded signal S', the signal S^* at the output of the Wyner-Ziv encoder is fed back to the MPEG decoder to serve as a more accurate reference frame for decoding of further frames. The systematic scheme described in Fig. 1 is compatible with systems already deployed, such as MPEG-2 digital TV broadcasting systems. The Wyner-Ziv bitstream can be ignored by legacy systems, but would be exploited by new receivers.

III. VIDEO DISTORTION MODEL

Decoded video quality delivered by the systematic lossy source-channel coding system is affected by three factors: the rate-distortion tradeoff of the main (systematic) encoder, the rate-distortion tradeoff of the Wyner-Ziv description, and the probability of packet loss. In this section, we model each of these effects. The important variables are defined in Table III below.

Symbol	Explanation
R_0	Bit-rate of systematic (main) encoder
D_0	MSE distortion corresponding to rate R_0
R_1	Bit-rate of Wyner-Ziv description
D_1	MSE distortion corresponding to rate R_1
R_{WZ}	Transmitted WZ bit-rate ($R_{WZ} \leq R_1$)
θ, R_m, D_m	Paramaters in encoder model (Sec III-A)
x_n^i	Original value of pixel i in frame n
$\hat{x}_n^i$	Systematic encoder's reconstruction of x_n^i
$\hat{\hat{x}}_n^i$	Wyner-Ziv encoder's reconstruction of x_n^i
$x_n'^i$	Wyner-Ziv decoder's reconstruction of x_n^i
D_n^{EE}	End-to-end distortion in decoded frame n
P$\{S\}$	Prob$\{$Video packet is lost or in error$\}$
P$\{F\}$	Prob$\{$WZ decoding of packet fails$\}$
$\mathcal{R}$	Total transmitted bit-rate
$\mathcal{D}$	Average end-to-end MSE distortion
$\mathcal{C}$	Allowable maximum bit-rate (capacity)

A. Wyner-Ziv Encoder Distortion

Following the analysis of [16], the rate distortion performance of a video encoder is modeled by the following parametric equation:

$$D = D_m + \theta/(R - R_m) \qquad (1)$$

where, D_m, R_m, and θ are parameters to be determined from three trial encodings. Using (1), we can find the rate-distortion pairs for the systematic video encoder, i.e., (R_0, D_0), as well as for the Wyner-Ziv video encoder, i.e., (R_1, D_1). It is important to note that the transmitted Wyner-Ziv bit-rate R_{WZ} is different from the bit-rate of the Wyner-Ziv description R_1 (See Fig. 2). Wyner-Ziv encoding involves coarse quantization followed by Slepian-Wolf encoding [17]. Coarse quantization reduces the encoding bit-rate to $R_1 \leq R_0$. Slepian-Wolf encoding, which is implemented using a channel encoder transmitting only parity (or syndrome) symbols further reduces the bit-rate to $R_{WZ} \leq R_1$.

B. End-to-End Distortion

We will now account for the distortion in the received video signal owing to packet loss, error concealment, and error propagation. Note that the error-propagation is due to the residual errors from error-concealment, as well as due to the quantization mismatch introduced by Wyner-Ziv decoding. Since we are concerned with modeling error propagation, the ensuing treatment assumes a video sequence consisting only of predictively encoded frames (P-frames). Modifications for intra-coded (I) frames and bidirectionally predicted (B) frames are straightforward.

In a typical video encoder, the pixel at location i in the nth frame is predicted from another pixel, say, at location j in the reconstruction of the previous frame, i.e., $\hat{x}_{n-1}^{j}$ serves as the predictor for x_n^i. Then the encoder and decoder's reconstruction of x_n^i are given by:

$$\begin{aligned} \hat{x}_n^i &= \hat{x}_{n-1}^j + v_n^i \\ x_n'^i &= x_{n-1}'^j + v_n^i \end{aligned} \tag{2}$$

where v_n^i denotes the unpredictable component, i.e., the error in the prediction of the current pixel, which is transformed, quantized, entropy-coded and transmitted to the decoder. When, instead of the main description, the Wyner-Ziv description is used to reconstruct the pixel in the current frame, then we have:

$$\begin{aligned} \hat{\hat{x}}_n^i &= \hat{x}_{n-1}^j + w_n^i \\ x_n''^i &= x_{n-1}'^j + w_n^i \end{aligned} \tag{3}$$

where w_n^i denotes the prediction error in the Wyner-Ziv (i.e., coarser) description. To mitigate mismatch between the video encoder and decoder, it is advantageous to use a locally decoded version of the compressed video signal as input to the Wyner-Ziv video encoder, rather than the original video signal, as modeled by (3) above. The probability $\mathrm{P}\{S\}$ as defined in Table III depends upon size of a video packet, the symbol error rate of the transmission channel and the channel characteristics. $\mathrm{P}\{F\}$ depends on the packetization method and on the Wyner-Ziv decoding procedure adopted for error-resilience. Since Wyner-Ziv decoding is used only when a packet is lost in the systematic transmission, $\mathrm{P}\{F\}$ matters only if the event S also occurs. For this reason, we are more interested in the conditional probability $\mathrm{P}\{F|S\}$. We have the following cases:

1) With probability $\mathrm{P}\{\bar{S}\} = 1 - \mathrm{P}\{S\}$, a packet is received and decoded correctly by the main (systematic) decoder and Wyner-Ziv decoding procedure is unnecessary. The only source of error energy in this case is the error propagation from previous frames, given by:

$$\begin{aligned} D_n^{EP} &= \mathrm{E}[(x_n^i - x_n'^i)^2] \\ &= \mathrm{E}[(x_n^i - \hat{x}_n^i)^2] + \mathrm{E}[(\hat{x}_n^i - x_n'^i)^2] \\ &= D_0 + \mathrm{E}[(\hat{x}_{n-1}^j - x_{n-1}'^j)^2] \\ &= D_0 + D_{n-1}^{EE} - D_0 = D_{n-1}^{EE} \end{aligned} \tag{4}$$

where it is assumed that the quantization error, $(x_n^i - \hat{x}_n^i)$ has zero mean and is independent of the error, $(\hat{x}_n^i - x_n'^i)$ introduced by the channel.

2) With probability $\mathrm{P}\{S\}(1 - \mathrm{P}\{F|S\})$, a packet is lost in the systematic transmission but Wyner-Ziv decoding is successful. Hence the error energy is contributed both by the coarser quantization in the decoded packet as well as by error propagation from the previous frames. The distortion contribution is given by:

$$\begin{aligned} D_n^{WZ} &= \mathrm{E}[(x_n^i - x_n''^i)^2] \\ &= \mathrm{E}[(x_n^i - \hat{\hat{x}}_n^i)^2] + \mathrm{E}[(\hat{\hat{x}}_n^i - x_n''^i)^2] \\ &= D_1 + \mathrm{E}[(\hat{x}_{n-1}^i - x_{n-1}'^i)^2] \\ &= D_1 + D_{n-1}^{EE} - D_0 \end{aligned} \tag{5}$$

with assumptions identical to those in (4).

3) With probability $\mathrm{P}\{S\}\,\mathrm{P}\{F|S\}$, a packet is lost in the systematic transmission and the Wyner-Ziv bit-rate is insufficient to reconstruct the lost packet. In this case, the packet is concealed using its co-located packet in the previous frame. The error energy is now contributed by the process of error concealment of the current packet as well as by the error propagation from the previous frames. The distortion contribution is then given by:

$$\begin{aligned} D_n^{EC} &= \mathrm{E}[(x_n^i - x_n'^i)^2] \\ &= \mathrm{E}[(x_n^i - x_{n-1}'^i)^2] \\ &= \mathrm{E}[(x_n^i - \hat{x}_{n-1}^i)^2] + \mathrm{E}[(\hat{x}_{n-1}^i - x_{n-1}'^i)^2] \\ &= \mathrm{E}[(x_n^i - \hat{x}_n^i)^2] + \mathrm{E}[\hat{x}_n^i - \hat{x}_{n-1}^i)^2] + D_{n-1} - D_0 \\ &= D_0 + MSE(n, n-1) + D_{n-1}^{EE} - D_0 \\ &= MSE(n, n-1) + D_{n-1}^{EE} \end{aligned} \tag{6}$$

where $MSE(n, n-1)$ is the mean-squared error between the reconstructed current and previous frames. The third equality assumes that the pixel variations, $(x_n^i - \hat{x}_{n-1}^i)$ are independent of the errors, $(\hat{x}_n^i - x_n'^i)$ introduced by the channel. The fourth equality assumes that quantization errors, $(x_n^i - \hat{x}_n^i)$ are independent of the pixel variations and have zero mean as before.

Using (4), (5) and (6) with the corresponding probabilities, the end-to-end distortion in the nth frame due to all of the above effects is then given by:

$$
\begin{aligned}
D_n^{EE} =& (1 - \mathrm{P}\{S\}) D_n^{EP} + \mathrm{P}\{S\}(1 - \mathrm{P}\{F|S\}) D_n^{WZ} \\
& + \mathrm{P}\{S\}\,\mathrm{P}\{F|S\} D_n^{EC}
\end{aligned} \tag{7}
$$

IV. SIMULATION RESULTS AND ANALYSIS

A. Experimental Setup

In this section we use the model equations to predict the performance of a practical Wyner-Ziv codec constructed from well-understood components viz., quantizers, entropy coders, and a Reed-Solomon (RS) codec. As shown in Fig. 2, The Wyner-Ziv encoding process consists of two stages:

1) A coarse quantizer operates on the quantized transformed prediction error signal generated by the conventional MPEG-2 encoder. The Wyner-Ziv description now consists of the entropy coded output of the coarse quantizer along with the motion vectors and mode decisions inherited from the conventional MPEG-2 encoder.
2) The resulting bitstream is input to a channel coder which applies systematic RS codes with byte-long symbols, across the slices of an entire frame. *Only the RS parity symbols* are then transmitted to the receiver, and these constitute the Wyner-Ziv bitstream. *The systematic portion of the RS encoder output is discarded.*

For a detailed description of this system, please refer to [3]. When transmission errors occur, the decoder generates a coarsely quantized version of the received prediction error signal. This coarse version is an error-prone copy of the Wyner-Ziv description, which serves as side information for the RS decoder. Using the parity symbols and error-prone Wyner-Ziv description, the RS decoder performs erasure decoding to obtain the error-free Wyner-Ziv description. A fallback mechanism substitutes the lost slices in the main video sequence with their correct but coarser versions. Then, using the distortion model developed in Section III, we have the following relations between the variables defined in Table III:

$$
\begin{aligned}
\mathcal{D} &= \frac{1}{N}\sum_{n=1}^{N} D_n^{EE}, \ldots N = \text{no. of frames in a GOP} \\
D_0 &= D_m + \theta/(R_0 - R_m) \\
D_1 &= D_m + \theta/(R_1 - R_m) \\
R_{WZ} &= [(n/k) - 1]R_1 \text{ with } n, k \in \mathbb{Z}^+ \text{ and } n \geq k \\
\mathcal{R} &= R_0 + R_{WZ} \\
\mathrm{P}\{S\} &= \mathrm{P}\{\text{slice is erased}\} \\
\mathrm{P}\{F\} &= \mathrm{P}\{\text{no. of slices erased} > n - k\}
\end{aligned} \tag{8}
$$

where, D_n^{EE} is obtained from (7), k is the number of slices per frame (1 slice = 1 packet) in the systematic transmission, and $n - k$ is the number of RS parity slices appended for error-resilience.

B. Results

To ascertain the accuracy of the proposed model, we compare the average end-to-end distortion predicted by the model to that calculated from actual experiments using the system of Fig. 2 over a range of symbol error probabilities. Fig. 3 plots the distortion for the Bus CIF sequence encoded at 30 frames per second with the *I-B-B-P* GOP structure. In this experiment, the systematic portion of the transmission consists of an MPEG video bitstream encoded at 1 Mbps. The Wyner-Ziv portion of the transmission consists of 111 Kbps of parity symbols in both the cases shown, but not in the error concealment case, which is shown for comparison only. The Wyner-Ziv description however, is different in each case. The data points on the plot are PSNR values averaged over 100 frames and for 25 different channel realizations at each symbol error probability. The worst performance is seen for FEC, where the Wyner-Ziv description is identical to the systematic description. When a coarser Wyner-Ziv description encoded at 500 Kbps is used but with the same Wyner-Ziv bit-rate of 111 Kbps, it provides stronger protection, and hence smaller distortion over a larger range of error rates than that provided by FEC. Note that the model closely conforms to the experimental data for all cases. Similar agreement between model and experiment is observed in Fig. 4 for the Foreman CIF sequence.

C. Analysis

At low symbol error rates, $P\{S\}$ is small, and the end-to-end distortion is dominated by D_n^{EP}, which contributes a small error-propagation term in (7). As the channel error probability increases, $P\{S\}(1-\mathrm{P}\{F|S\})$ increases and the distortion is dominated by the D_n^{WZ} term which accounts for the propagation of the quantization mismatch resulting from Wyner-Ziv decoding. This is manifested as a small but visually imperceptible drop in PSNR in Figs. 3 and 4. When the channel error probability increases further, the Wyner-Ziv bit-rate R_{WZ} is no longer sufficient to protect the video waveform from channel errors. The distortion is now dominated by the D_n^{EC} term which accounts for error concealment and error propagation. At this high error probability, D_n^{EC} is very large and the picture quality degrades rapidly. Even though the model accurately predicts the *average* distortion at the receiver, it is instructive to observe the instantaneous effect of Wyner-Ziv decoding and error concealment on the decoded video quality. Figs. 5 and 6 show a decoded video frame in the Bus sequence, at low and high symbol error probability. Clearly, the residual errors from coarse Wyner-Ziv quantization in the lossy forward error protection scheme are visually more pleasing

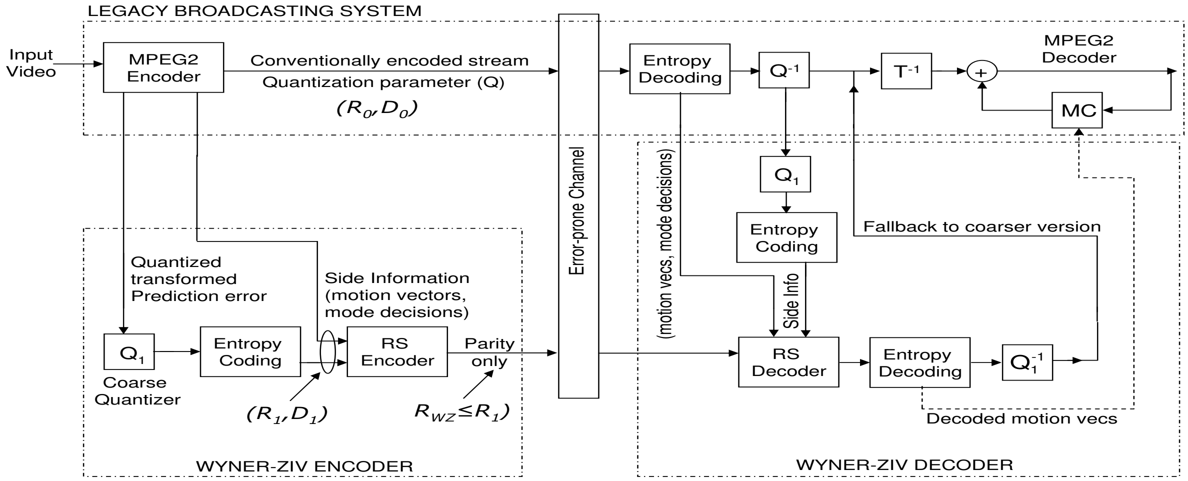

Fig. 2. Implementation of systematic forward error protection by combining MPEG coding and Reed-Solomon codes across slices.

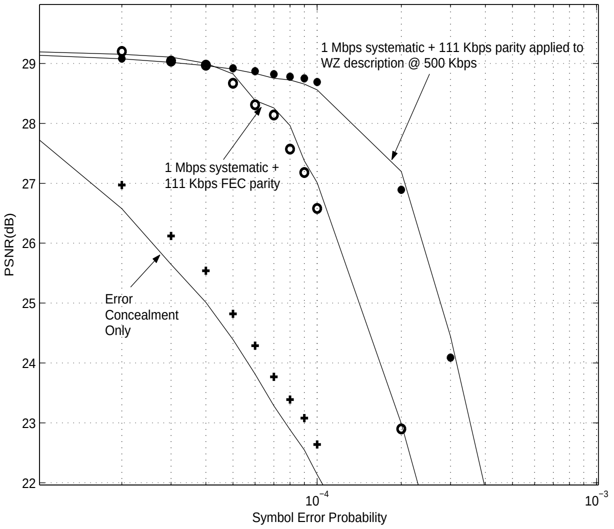

Fig. 3. Comparison of (1) Systematic lossy source-channel coding with a Wyner-Ziv description, (2) Conventional forward error correction (FEC), and (3) Error concealment only, for the Bus.CIF sequence. For each case, the data-points are obtained from actual simulations, while the solid line shows the distortion calculated from the model. Note that systematic lossy source channel coding outperforms traditional FEC at symbol error rates higher than 4×10^{-5}.

than the residual errors from error concealment caused by the failure of the FEC scheme.

D. Optimization

As in any joint source channel coding problem, the decoded video quality delivered by the systematic lossy source channel coding system depends not only upon the total transmitted bit-rate $\mathcal{R}$, but also on the allocation of bits between the source rate R_0 and the Wyner-Ziv bit-rate R_{WZ}. Additionally, and unlike FEC bit-allocation problems, the decoded video quality depends upon which Wyner-Ziv description (R_1, D_1) is employed. Clearly, deciding the Wyner-Ziv bit-rate R_{WZ} alone and choosing the Wyner-Ziv description arbitrarily is insufficient. If R_1 is too large, then error-resilience is compromised at high symbol error probabilities. If R_1 is too small, i.e., if the Wyner-Ziv description is too coarse, then the component D_n^{WZ} contributes a large distortion term to (7) and therefore nullifies the advantage of Wyner-Ziv decoding. Thus the optimization problem involves finding the encoding bit-rates R_0 and R_1 and the transmitted Wyner-Ziv bit-rate R_{WZ} which result in the minimum end-to-end distortion at the given symbol error probability. For this, we can use the system of equations (8) to minimize $\mathcal{D}$, such that $\mathcal{R} = R_0 + R_{WZ} = R_0 + (\frac{n}{k} - 1)R_1 \leq \mathcal{C}$.

V. SUMMARY

We have proposed a simple model to describe the relation between the total transmission bit-rate and the end-to-end video quality delivered by the systematic lossy source channel coding system. As borne out by the model equations and the experimental results, resilience to channel errors is achieved by transmitting a supplementary bitstream generated by Wyner-Ziv encoding of the original video signal. The Wyner-Ziv scheme allows for some residual end-to-end distortion, and can therefore transmit at a much lower bit-rate than traditional FEC, while providing gracefully deteriorating video quality with worsening channel conditions. Since the distortion predicted by the model is very close to that observed in experiments, the model equations can be used to determine the bit-rates at which

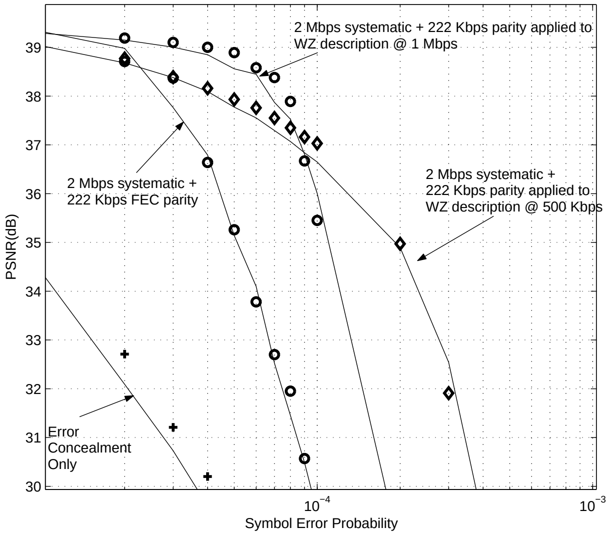

Fig. 4. Comparison of (1) Systematic lossy source-channel coding with a finer Wyner-Ziv description, (2) Systematic lossy source-channel coding with a coarser Wyner-Ziv description, (3) Conventional forward error correction (FEC), and (4) Error concealment only, for the Foreman.CIF sequence. For each case, the data-points are obtained from actual simulations, while the solid line shows the distortion calculated from the model. Note that systematic lossy source channel coding outperforms traditional FEC at symbol error rates higher than 10^{-5}.

(a) FEC @ SER = 10^{-4} (b) WZ @ SER = 10^{-4}

Fig. 5. Quantization mismatch in the lossy forward error protection scheme is more tolerable than concealment errors in traditional FEC.

the Wyner-Ziv description is encoded and transmitted, in order to minimize average end-to-end distortion at a given channel error probability.

ACKNOWLEDGMENT

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(a) FEC @ SER = 2×10^{-4} (b) WZ @ SER = 2×10^{-4}

Fig. 6. Substantial improvement in decoded video quality over FEC schemes is observed at high error probabilities

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