Systematic Lossy Error Protection versus Layered Coding with Unequal Error Protection

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ABSTRACT

In this paper we compare two schemes for error-resilient video transmission, viz., systematic lossy error protection, and scalable coding with unequal error protection. In the first scheme, the systematic portion consists of the compressed video signal transmitted without channel coding. For error-resilience, an additional bitstream generated by Wyner-Ziv encoding of the video signal is transmitted. In the event of channel errors, the Wyner-Ziv description is decoded using the error-prone systematic description as side-information. In the second scheme, the video bitstream is partitioned into two or more layers, and each layer is assigned different amounts of parity information depending upon its relative significance. Since the base layer has heavy protection, a certain minimum video quality is guaranteed at the receiver. We compare experimentally, the performance of the competing schemes, for a particular application, i.e., Error-resilient digital video broadcasting. It is shown that systematic lossy error protection ensures graceful degradation of video quality without incurring the loss in rate-distortion performance characteristic of practical layered video coding schemes.

Keywords: Wyner-Ziv coding, systematic coding, systematic lossy error protection, layered (scalable) coding, unequal error protection.

1. INTRODUCTION

In typical video transmission systems, a video bitstream is compressed using MPEG1/2/4 or H26x and is transmitted to one or more receivers. Error-resilience is achieved either by some form of forward error correction (FEC) or by employing automatic retransmission requests (ARQ) where feedback is available. In systems relying solely on FEC, e.g., video broadcasting systems, the channel code along with decoder based error-concealment ensures that the video quality is acceptable for the given channel conditions. However, when the channel error rate exceeds the error correction capability of the FEC codes, channel coding fails to protect the bitstream and the video quality degrades rapidly, giving rise to what is known as the "cliff" effect. In this paper we compare two methods used to mitigate the cliff effect and ensure graceful degradation of video quality with increasing channel error rates. The first method, scalable coding with unequal error protection, is a natural extension of FEC-based systems and involves partitioning the video bitstream into layers of varying significance, with each layer assigned an amount of channel coding protection proportional to its importance. This ensures that, as the channel conditions worsen, the less important portion of the bitstream (enhancement layer) cannot be decoded but the more important information (base layer) can still be decoded, guaranteeing a certain minimum video quality at the receiver. The second method is based on our recent work on systematic lossy source-channel coding of video waveforms [1, 2]. In this scheme, the video bitstream transmitted unprotected over the error-prone channel constitutes the systematic portion of the transmission. In addition, a supplementary bitstream is generated using Wyner-Ziv encoding of the video sequence. This Wyner-Ziv bitstream contains a coarse description of the original video sequence. In the event

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Image and Video Communications and Processing 2005, edited by Amir Said,
John G. Apostolopoulos, Proc. of SPIE-IS&T Electronic Imaging,
SPIE Vol. 5685 © 2005 SPIE and IS&T · 0277-786X/05/$15

of channel errors, Wyner-Ziv decoding is performed at the decoder to recover this coarse description, using the received error-prone systematic transmission as side information. Thus, the systematic lossy source-channel coding is used to correct channel errors up to a certain residual distortion determined by the coarseness of the Wyner-Ziv description. It has been shown that this scheme outperforms FEC by providing acceptable video quality over a wide range of symbol error rates. For this paper, we are interested in comparing the two schemes by observing their performance for a particular application, viz., digital video broadcasting.

2. PREVIOUS WORK

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 [3–5]. 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 [6] 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 [7]. 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 [7].

The systematic coding framework was used by Pradhan and Ramchandran [8] 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 [9], followed by an improved practical Wyner-Ziv codec [1, 2], 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 [10–14]. 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.

A layered coding scheme has the advantage that a single compression scheme can be used to generate a bitstream which can be decoded by users with different bandwidth capabilities, with higher bandwidth users getting better video quality. In conjunction with Priority Encoding Transmission [15, 16], layered video coding schemes have been proposed [17–27] which provide graceful degradation of video quality with worsening channel conditions. However, these schemes are not used in practical broadcasting systems due to inferior rate-distortion performance. In this work, we show that systematic lossy error protection does not suffer from this limitation and therefore is an attractive option for practical video transmission systems.

The remainder of this paper is organized as follows. The principle of systematic lossy error protection (SLEP) is explained in Section 3. Section 4 describes a practical system for implementing the SLEP scheme for digital video broadcasting. In Section 5, we compare the performance of the lossy error protection with that of layered coding with unequal error protection by experimentally simulating a broadcasting scenario.

3. SYSTEMATIC LOSSY FORWARD ERROR PROTECTION 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'.

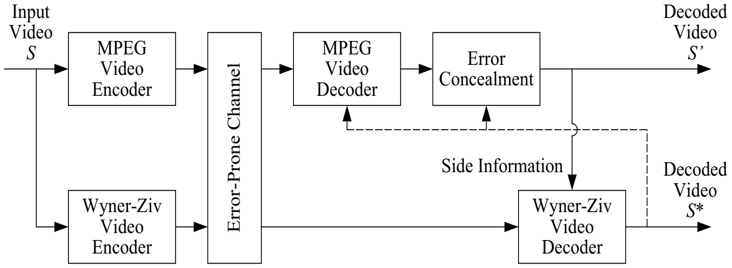


Figure 1. Wyner-Ziv decoder uses decoded error-concealed video waveform as side information in systematic lossy source-channel setup.

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.

4. PRACTICAL SCHEME FOR SYSTEMATIC LOSSY ERROR PROTECTION

We presented first results of error-resilient video broadcasting with pixel-domain Wyner-Ziv coding [9, 28], and then with an improved Wyner-Ziv video codec which used a hybrid video codec with Reed-Solomon (RS) codes [1]. For a practical Wyner-Ziv codec, consider the forward error protection scheme shown in Fig. 2. The Wyner-Ziv codec uses a hybrid video codec in which the video frames are divided into the same slice structure as that used in the MPEG video coder, but are encoded with coarser quantization.

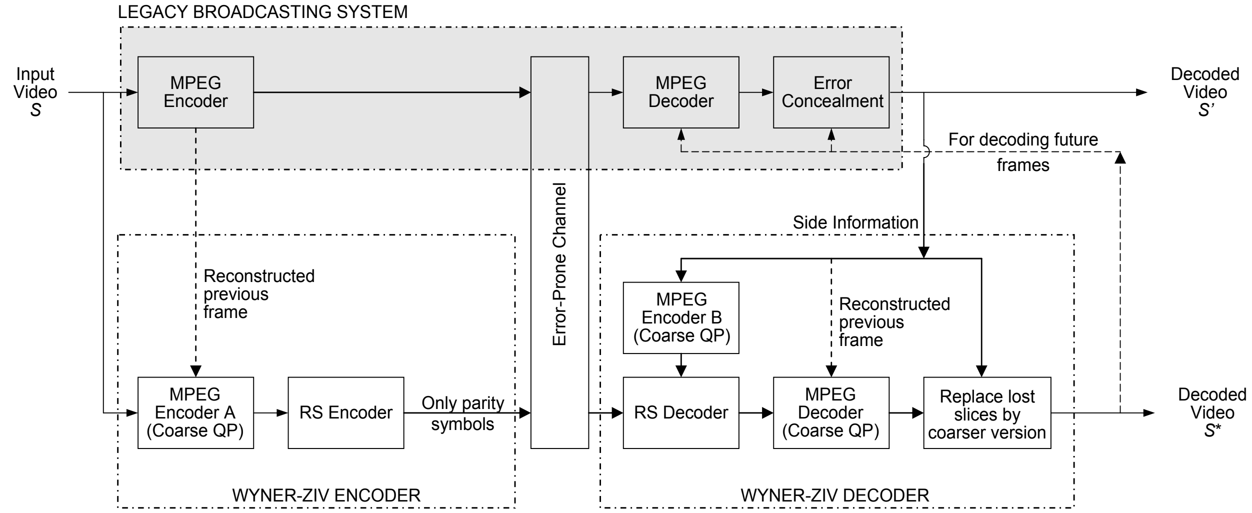


Figure 2. Implementation of SLEP by combining hybrid video coding and Reed-Solomon Slepian-Wolf coding.

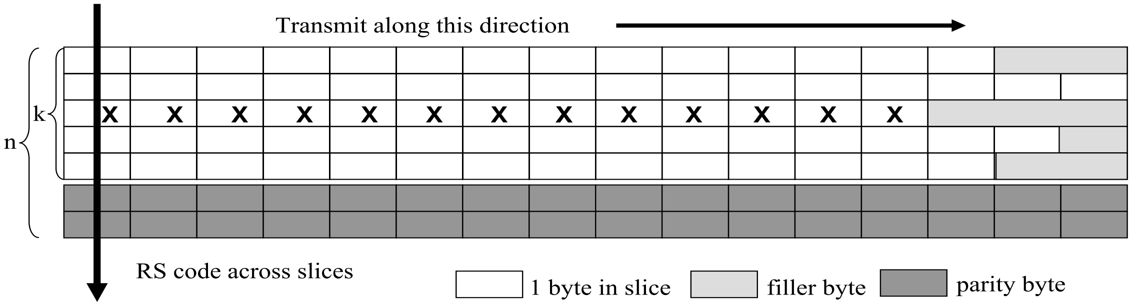


Figure 3. Reed-Solomon codes are applied across the slices of the (coarse) Wyner-Ziv description, and only the parity bits are transmitted, constituting the Wyner-Ziv bitstream.

The bitstream from this "coarse" encoder A, referred to as the Wyner-Ziv description, is input to a channel coder which applies RS codes across the slices of an entire frame, as shown in Fig. 3. *Only the RS parity symbols* are transmitted to the receiver. When transmission errors occur, the conventionally decoded error-concealed video S' is re-encoded by a coarse encoder B, which is a replica of the coarse encoder A. Therefore, the output of this coarse encoder B is identical to that of coarse encoder A except for those slices which are corrupted by channel errors. Since the locations of the erroneous slices are known, the RS decoder treats them as erasures and applies erasure decoding to recover the missing coarse slices. These coarse slices then replace the corrupted slices in the main video sequence. This causes some prediction mismatch which propagates to the subsequent frames, but visual examination of the decoded sequence shows that this small error is imperceptible. Thus, the receiver obtains a video output S^* of superior visual quality, using the conventionally decoded, error-concealed sequence as side information. This system includes FEC as a special case, which is realized by forcing both encoders in Fig. 2 to use the same quantization parameter. To mitigate prediction mismatch between the two coarse video encoders A and B, the coarse encoder A must use the locally decoded previous frame from the "main" MPEG encoder, as a reference for predictive coding. To simplify the Wyner-Ziv decoding process, we force the Wyner-Ziv description to use the same motion vectors and mode decisions as the systematic description. This reduces the coarse video encoders A and B to simple (coarse) quantizers, and greatly reduces the complexity of Wyner-Ziv decoding.

5. EXPERIMENTAL RESULTS

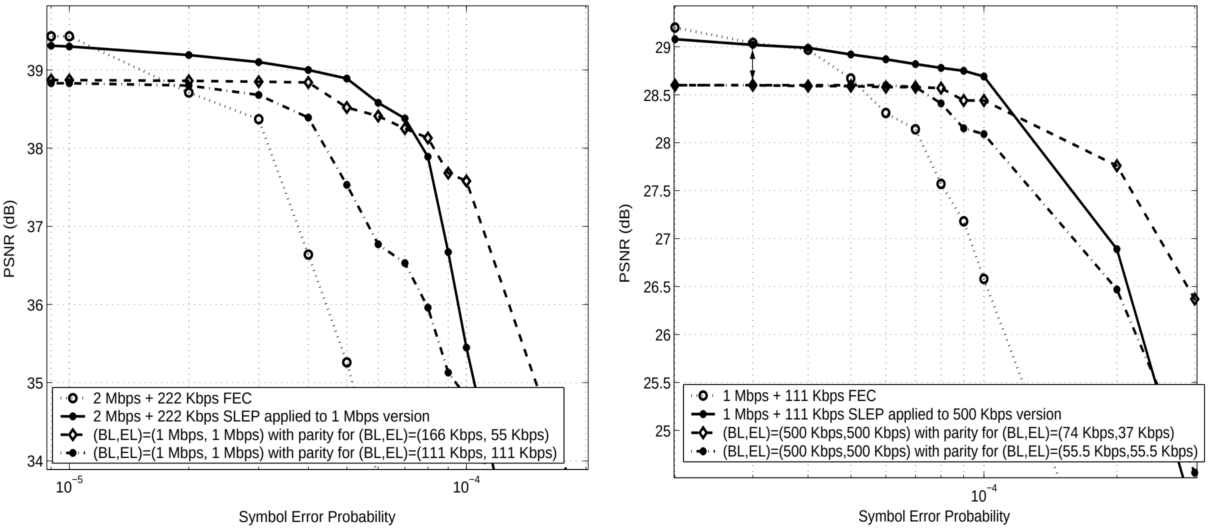
We now compare the end-to-end video quality delivered by systematic lossy error protection (SLEP) with that obtained using layered coding with unequal error protection (LCUEP).

For both schemes, the I-B-B-P GOP structure is used, with one video slice consisting of one row of macroblocks. In SLEP, identical slice structure is used for the main and Wyner-Ziv descriptions, to facilitate Wyner-Ziv decoding as explained above. When Wyner-Ziv decoding is unsuccessful, i.e., when the Wyner-Ziv bit-rate is insufficient to decode the Wyner-Ziv bitstream, previous frame error concealment is used. In LCUEP, when an enhancement layer slice in LCUEP cannot be recovered using the parity bit-rate assigned to it, the base layer reconstruction of that slice is used wherever available. If the base layer slice is also not recoverable, then previous frame error concealment is used.

For SLEP, we use the *Foreman CIF* sequence encoded at 2 Mbps as the systematic portion of the transmission. To illustrate the tradeoff between the error-resilience achieved and the residual distortion resulting from Wyner-Ziv decoding, we employ a (coarse) Wyner-Ziv description encoded at 1 Mbps. The Wyner-Ziv bit-rate, which is the bit-rate of the RS parity symbols, is restricted to 222 Kbps, for a total transmitted bit-rate of 2 Mbps + 222 Kbps = 2.222 Mbps.

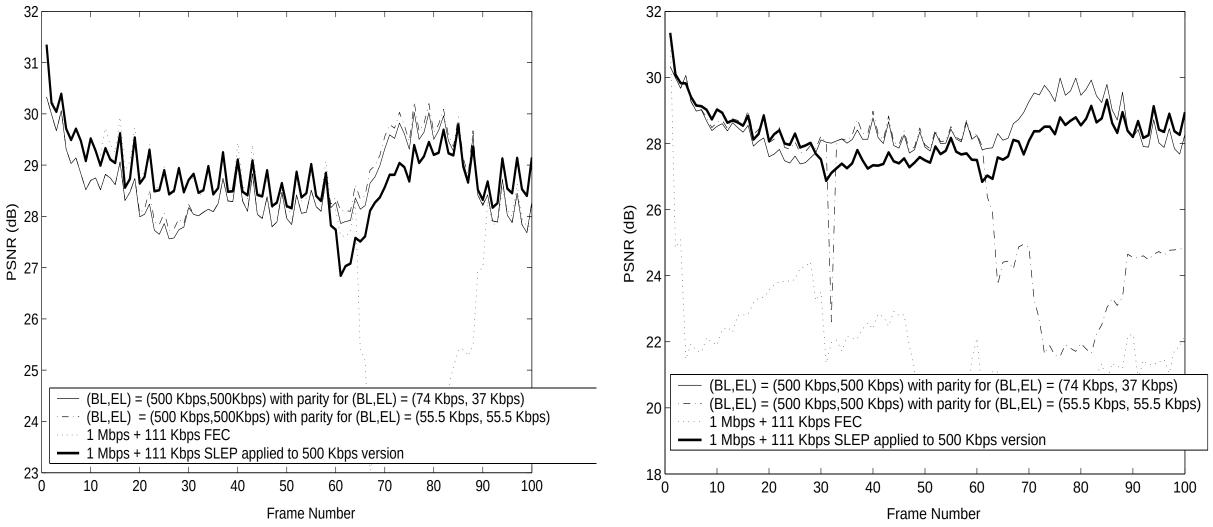
For LCUEP, we use the same sequence encoded using a 2-layer MPEG-2 SNR scalable encoder, with a total encoding rate of 2 Mbps. Error-resilience is again achieved by using RS codes across the slices of the video frames, and the total parity bit-rate is restricted to 222 Kbps as before. We observe the performance of this scheme for different allocations of the parity bit-rate among the base and enhancement layers, such that the total bit-rate of the scalable bitstream and their respective parity streams is again 2.222 Mbps. Note that for SLEP, only the parity symbols corresponding to the Wyner-Ziv description are transmitted, while for the LCUEP scheme, parity symbols corresponding to both the base layer and the enhancement layer (if protected) need to be transmitted.

Consider the average end-to-end video quality (PSNR) as the symbol error rate of the channel increases. Fig. 4(a) compares the performance of SLEP with a 1 Mbps Wyner-Ziv description to that of a layered coding scheme with (Base Layer (BL), Enhancement Layer (EL)) = (1 Mbps, 1 Mbps). The performance of FEC is also shown for comparison. Clearly, FEC shows the least error-resilience and the PSNR drops drastically beyond a symbol error rate of 3×10^{-5}. Equal error protection, which assigns 111 Kbps of parity



(a) (b)

Figure 4. Systematic lossy error protection (SLEP) provides graceful degradation of video quality when the symbol error rate increases, without incurring the loss in rate-distortion performance characteristic of practical layered (scalable) video coding schemes.



(a) Frame PSNRs @ error probability = 6×10^{-5} (b) Frame PSNRs @ error probability = 2×10^{-4}

Figure 5. At high symbol error probabilities, SLEP and LCUEP both provide higher error-resilience than FEC or equal error protection. At low symbol error probabilities, SLEP provides superior decoded picture quality as compared to LCUEP, because of poor compression efficiency of practical scalable video codecs.

(a) FEC (26.5 dB) (b) Layered Coding (28.4 dB) (c) SLEP (28.7 dB)

Figure 6. A decoded frame from a channel trace at error probability 10^{-4} in Fig. 4(b) is shown here for visual comparison. Transmission errors result in lost video slices, which are concealed by RS channel coding for FEC, unequal error protection with RS codes for LCUEP, and Wyner-Ziv decoding with RS Slepian-Wolf coding applied to a coarse Wyner-Ziv description for SLEP. When the parity bit-rate is insufficient, previous frame error concealment is used.

bit-rate each, to the base and enhancement layers, has stronger error resilience than FEC. This is because the video slices in each individual layer are smaller than those in the non-scalable transmission, and hence have a smaller probability of being lost. Unequal error protection, which assigns 166 Kbps of parity bit-rate to the base-layer and the remainder to the enhancement layer has the best performance in terms of error resilience but scalable coding suffers a loss in PSNR at low symbol error rates. The SLEP scheme with a 1 Mbps Wyner-Ziv description has slightly lower error-resilience because it uses the longer slices of the non-scalable 2 Mbps description in the systematic part of the transmission, but it benefits from the efficient rate-distortion performance of the non-scalable description. Hence SLEP does not suffer an appreciable loss in rate-distortion performance at low symbol error rates.

Similar trends are observed for the *Bus CIF* sequence transmitted at a total source bit-rate of 1 Mbps, as shown in Fig. 4(b). In this case, SLEP consists of 111 Kbps of RS parity symbols applied to a Wyner-Ziv description encoded at 500 Kbps. The LCUEP scheme consists of (BL, EL) = (500 Kbps, 500 Kbps), with parity assigned to the two layers such that the total parity bit-rate is again 111 Kbps. As before, SLEP provides slightly lower resilience than LCUEP, but, unlike LCUEP, it does not register an appreciable drop in PSNR at low symbol error rates. This effect can also be appreciated by observing frame PSNRs for a channel trace at low and high symbol error probabilities, as shown in Fig. 5. Fig. 6 compares the decoded picture quality obtained using traditional FEC with that obtained using SLEP and LCUEP.

6. CONCLUSIONS

In this paper, we have compared systematic lossy error protection and layered coding with unequal error protection. When tested in a practical application scenario, namely digital video broadcasting, both schemes provide superior error resilience compared to traditional FEC. Practical layered (scalable) coding achieves graceful degradation of video quality at high error rates, but has poor compression efficiency, resulting in inferior picture quality at low error rates. Systematic lossy error protection not only provides graceful degradation of video quality but also retains the efficient rate-distortion performance of conventional non-scalable codecs, resulting in superior decoded picture quality at low error rates.

ACKNOWLEDGMENTS

This work has been supported by NSF Grant No: CCR-0310376.

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