Systematic Lossy Error Protection for Video Transmission over Wireless Ad Hoc Networks

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ABSTRACT

Wireless ad hoc networks present a challenge for error-resilient video transmission, since node mobility and multipath fading result in time-varying link qualities in terms of packet loss ratio and available bandwidth. In this paper, we propose to use a systematic lossy error protection (SLEP) scheme for video transmission over wireless ad hoc networks. The transmitted video signal has two parts - a systematic portion consisting of a video sequence transmitted without channel coding over an error-prone channel, and error protection information consisting of a bitstream generated by Wyner-Ziv encoding of the video sequence. Using an end-to-end video distortion model in conjunction with online estimates of packet loss ratio and available bandwidth, the optimal Wyner-Ziv description can be selected dynamically according to current channel conditions. The scheme can also be applied to choose one path for transmission from amongst multiple candidate routes with varying available bandwidths and packet loss ratios, so that the expected end-to-end video distortion is maximized. Experimental results of video transmission over a simulated ad hoc wireless network shows that the proposed SLEP scheme outperforms the conventional application layer FEC approach in that it provides graceful degradation of received video quality over a wider range of packet loss ratios and is less susceptible to inaccuracy in the packet loss ratio estimation.

Keywords: Wyner-Ziv coding, systematic lossy source-channel coding, video transmission, ad hoc wireless network

1. INTRODUCTION

An ad hoc wireless network consists of a collection of wireless nodes without a fixed infrastructure. The fast and flexible deployment of such a system is appealing to many application scenarios from search-and-rescue operations to high way automation. To support real-time video streaming over an ad hoc network, many technical issues need to be solved. The wireless channel conditions typically fluctuate over time and can be severely degraded due to multipath fading and shadowing; routing becomes a challenging task as user mobility leads to a dynamic network topology. In addition, video streaming typically imposes stringent rate and latency requirements, and the decoded video quality is sensitive to packet losses in the network because of error propagation in the compressed bitstream.

Therefore, some form of protection is needed to support video transmission over the wireless ad hoc network. For live streaming scenarios, application layer forward error correction (FEC) is generally preferred over retransmission schemes such as hybrid ARQ [1], as retransmitted video packets may not satisfy a tight playout deadline. The drawback of the FEC approach, however, is that the amount of protection provided by the parity packets needs to match closely with the packet loss ratio (PLR) over the network. Overestimation of the PLR introduces unnecessary redundancy of the transmitted stream, whereas underestimation would lead to complete failure of the error correction procedure. This is usually termed as the *cliff effect* of FEC. Over an wireless ad hoc network with time-varying channel conditions, although one can switch between different FEC protection levels according to the observed or estimated packet loss ratio, the failure of protection caused by inaccuracy of the estimation is still undesirable.

To overcome this problem, we propose to apply systematic lossy error protection (SLEP) to error-resilient video transmission over ad hoc wireless networks. Based on ideas of Wyner-Ziv video coding [2], the proposed

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SLEP scheme results in graceful degradation of decoded video quality over a wide range of packet loss ratios, hence avoiding the cliff effect of FEC [3, 4]. In this work, we compare the performance of SLEP with the conventional FEC, and show that as packet loss ratio needs to be estimated and updated over time, the proposed SLEP scheme is less susceptible to estimation inaccuracy, and yields better visual quality in the decoded video when packet loss occurs. When multiple paths are available in the network, we present a simple optimization procedure for choosing the most appropriate path.

The remainder of this paper is organized as follows. Section 2 provides a brief survey of research related to systematic lossy error protection. In Section 3, we describe the principle and implementation of systematic lossy error protection (SLEP). Section 4 explains how estimation of packet loss ratio and available bandwidth is performed over the wireless ad hoc network and how we select the most appropriate Wyner-Ziv description in the SLEP scheme based on a video distortion model. Experimental results for video transmission over a simulated ad hoc wireless network are presented in Section 5. Specifically, the results illustrate the dynamic switching between Wyner-Ziv descriptions according to observed channel conditions, and the selection of a transmission route among multiple available paths in the network.

2. RELATED WORK

The lossy error protection method discussed in this paper is based on the theoretical framework of systematic lossy source-channel coding [5]. 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 [5]. Their proof uses the Wyner-Ziv's results on lossy compression with side information available only at the decoder [6–8] - specifically, a single letter characterization of the rate-distortion function for source coding with decoder side information, and the observation that this rate-distortion function is greater than or equal to the rate-distortion function for source coding with side information available to both the encoder and the decoder.

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 using a practical Wyner-Ziv codec [3, 4, 10], 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 decoding 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.

3. SYSTEMATIC LOSSY ERROR PROTECTION

3.1. Principle

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. 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 fully redundant, i.e., it can be regenerated bit-by-bit at the decoder, using the decoded video S'. When transmission errors occur, Wyner-Ziv bits is needed for error-free reconstruction of the coarser second description, employing the decoded video signal S' as side information. 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.

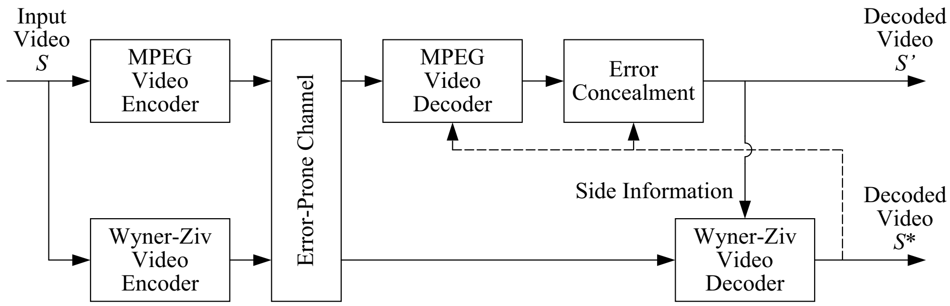

Figure 1. Wyner-Ziv decoder uses decoded error-concealed video waveform as side information in systematic lossy source-channel setup.

3.2. Implementation of a SLEP system

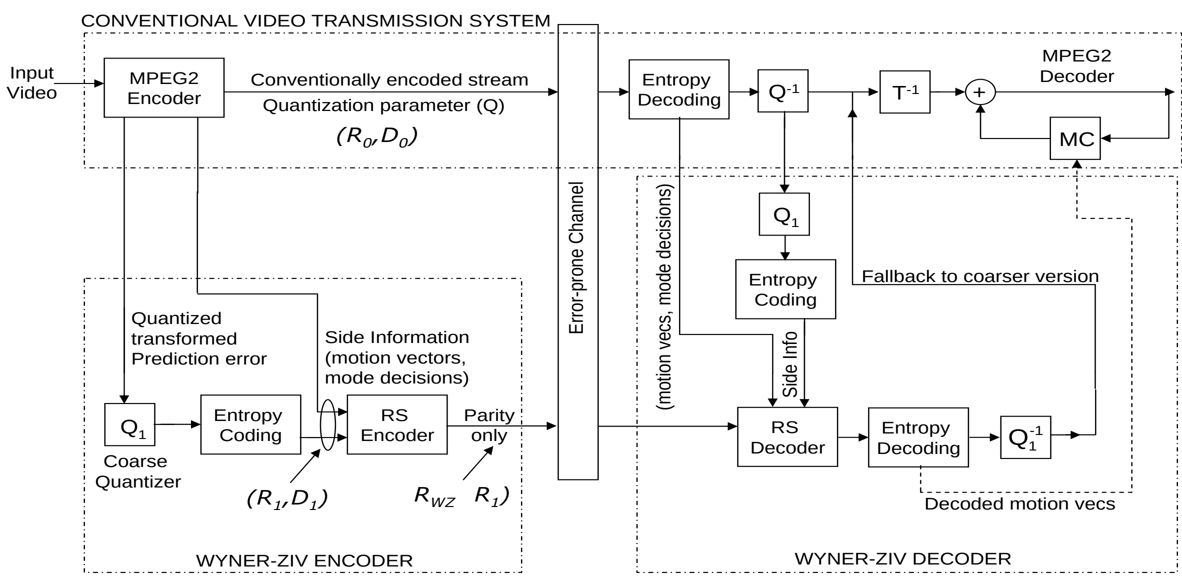

Figure 2. Implementation of systematic forward error protection by combining MPEG coding and Reed-Solomon codes across video packets.

In this paper, the Wyner-Ziv video description is generated by coarsely quantizing and entropy coding the transformed prediction error signal from the main MPEG codec, and combining it with motion vectors and mode decisions inherited from the main MPEG codec. A Reed-Solomon (RS) Slepian-Wolf encoder then applies byte-long RS codes across several packets of the Wyner-Ziv video description and transmits *only the parity symbols* as the Wyner-Ziv bitstream. The complete system including the systematic transmission and the Wyner-Ziv video codec is shown in Fig. 2. For further details about the implementation, please refer to [4]. The only difference between the implementations is that in [4], the RS codes are applied across the slices of a video frame, while in the this work, RS codes are applied across several video packets, each of which can span over several slices.

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 packets in the main video sequence with their correct but coarser counterparts. The video distortion is thus limited to a small residual value determined by the coarse quantization performed in the Wyner-Ziv encoder.

4. SLEP OVER AD HOC WIRELESS NETWORKS

In an ad hoc wireless network, the SLEP scheme must update its estimate of the packet loss ratio and select an appropriate combination of the main (systematic) and Wyner-Ziv video descriptions. For consistency in the received video quality, we propose to maintain a constant rate for the main description, while switching the Wyner-Ziv descriptions to minimize the end-to-end distortion, according to the observed packet loss ratio and total rate constraint. In this section, we first explain the process of estimating the packet loss ratio and available bandwidth, followed by selection of the appropriate Wyner-Ziv description.

4.1. Estimation of Network Condition

Given the rate of the main description, the allowed rate of parity information depends on the available bandwidth C_{avail} over the chosen route, whereas the choice of the protection level is determined by the packet loss ratio P_{loss} over the path. As link qualities and user behaviors change dynamically in a wireless network, an online estimate is needed for both quantities.

To estimate C_{avail}, packet arrivals and departures are logged at each node, and a local estimate of the link capacity and flow rate is obtained by averaging over past observations. Specifically, for a given period of time T_{total} on each node, we denote T_{busy} as the total time that the node spends for transmitting the packets, including MAC layer overhead, T_{block} as the average time during which the node is blocked from transmission either due to the presence of other transmissions or due to the back-off procedure in the carrier sense and collision avoidance mechanism, and T_{idle} as the total time for which the node remains idle and ready for transmission:

$$T_{total} = T_{busy} + T_{block} + T_{idle}. \tag{1}$$

Consequently, the flow rate for Stream s on Node n can be estimated as:

$$F_{n,s} = \frac{B_s}{T_{total}} = \frac{B_s}{T_{busy} + T_{block} + T_{idle}}. \tag{2}$$

where B_s is the total packet size from stream s over the period. The estimated bandwidth over that node is*:

$$C_n = \frac{\sum_s B_s}{T_{busy} + T_{block}}, \tag{3}$$

which takes into account packets from all streams. For Stream s, the available bandwidth becomes:

$$C_{n,s} = C_n - \sum_{s' \neq s} F_{n,s'}. \tag{4}$$

where the $F'_{n,s'}s$ denote the existing traffic rates from other streams on that node. For a given path $\mathcal{P}_f$ from source to destination, the end-to-end available bandwidth corresponds to the bottleneck value:

$$C_{avail} = \min_{n \in \mathcal{P}_f} C_{n,s}. \tag{5}$$

*Due to the broadcast nature of the wireless medium, and the fact that traffic for different destinations share the same queue on a wireless terminal. We therefore estimate the capacity for each *node*, instead of for each *link*, as the average service rate to the queue.

Table 1. Variables used to model the end-to-end video distortion in the SLEP scheme.

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	Parameters in encoder model (to be explained below)
D_n^{EE}	End-to-end distortion in decoded frame n
$\mathrm{P}\{S\}$	Prob{Video packet is lost or in error}
$\mathrm{P}\{F\}$	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)

Since $C'_{n,s}s$ can be estimated locally at each node for each stream, the final value of C_{avail} can be collected from source to destination by comparing the local available bandwidth at each intermediate node. In contrast, estimation of the packet loss ratio P_{loss} is performed in an end-to-end fashion. By counting the number of received packets and inducing the number of lost packets from discontinuous sequence numbers, the receiver keeps a running average of the estimated packet loss ratio, and feeds back this information to the sender via acknowledgment packets.

4.2. Selection of Best Video Description

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 model presented here is based on our work presented in [10] in the context of video broadcasting, with a slight modification to account for the different packetization scheme used in this paper. The derivation of the expressions for the distortion terms in the model equations, as well as the underlying assumptions have been explained in detail in [10]. Hence, in the sequel, we present only the final expressions and focus on the selection of the optimal Wyner-Ziv video description. Relevant model variables are defined in Table 1.

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

$$D = D_m + \theta/(R - R_m) \tag{6}$$

where the parameters D_m, R_m, and θ can be determined from trial encodings. Using (6), 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).

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.

The probability $\mathrm{P}\{S\}$ as defined in Table 1 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 $P\{\bar{S}\} = 1 - P\{S\}$, 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:

$$D_n^{EP} = D_{n-1}^{EE} \tag{7}$$

2. With probability $P\{S\}(1 - P\{F|S\})$, 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 modeled by:

$$D_n^{WZ} = D_{n-1}^{EE} + D_1 - D_0 \tag{8}$$

3. With probability $P\{S\} P\{F|S\}$, a packet is lost in the systematic transmission and the Wyner-Ziv bitrate 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 modeled by:

$$D_n^{EC} = MSE(n, n-1) + D_{n-1}^{EE} \tag{9}$$

Using (7), (8) and (9) with the corresponding probabilities, the end-to-end distortion in the n^{th} frame due to all of the above effects is given by:

$$D_n^{EE} = (1 - P\{S\})D_n^{EP} + P\{S\}(1 - P\{F|S\})D_n^{WZ} + P\{S\} P\{F|S\}D_n^{EC} \tag{10}$$

The model described above was originally developed for the case in which one video packet corresponds to a video slice, i.e., to one row of macroblocks. To reduce the overhead of MAC header transmission over the ad hoc wireless network, the video slices are grouped into larger packets, typically around 1500 bytes. Thus one video packet can contain several slices, and may span over frame boundaries. Consequently, the loss of a packet results in the loss of several video slices. The distortion due to Wyner-Ziv decoding and error concealment is therefore more severe than those modelled for i.i.d. slice losses in equations (8) and (9). To account for this effect, we introduce a correcting factor $\beta > 1$, in the equations for Wyner-Ziv decoding and error concealment, as follows:

$$\begin{aligned} D_n^{WZ} &= D_{n-1}^{EE} + \beta(D_1 - D_0) \\ D_n^{EC} &= D_{n-1}^{EE} + \beta MSE(n, n-1) \end{aligned} \tag{11}$$

This parameter needs to be tuned only once beforehand for the packet loss rates under consideration, and a value of $\beta = 1.5$ is chosen to yield model distortion values within 0.5 dB of the actual end-to-end distortions. Using the above model, the rate distortion performance of the SLEP system of Fig. 2, can be described by the following relations between the quantities defined in Table 1:

$$\begin{aligned} \mathcal{D} &= \frac{1}{N}\sum_{n=1}^{N} D_n^{EE}, ...N = \text{no. of frames in a GOP} \\ D_0 &= D_m + \theta/(R_0 - R_m) \\ D_1 &= D_m + \theta/(R_1 - R_m) \\ R_{WZ} &= [(n/k) - 1]R_1 \text{ with } n, k \in \mathbb{Z}^+ \text{ and } n \geq k \\ \mathcal{R} &= R_0 + R_{WZ} \\ P\{S\} &= P\{\text{packet containing the video slices is lost}\} \\ P\{F\} &= P\{\text{no. of packets lost} > n - k\} \end{aligned} \tag{12}$$

where D_n^{EE} is obtained from (10), n and k are the parameters of the RS code. Thus $n - k$ is the number of RS parity slices which are finally transmitted in the Wyner-Ziv bitstream. For a fixed systematic description (R_0, D_0), the best Wyner-Ziv description (R_1, D_1) can now be obtained by minimizing $\mathcal{D}$ such that $\mathcal{R} < \mathcal{C}$.

5. EXPERIMENTAL RESULTS

We evaluate the performance of SLEP over a simulated wireless ad hoc network using the Network Simulator (ns-2) [17]. As shown in Fig. 3, The network consists of 25 wireless nodes randomly placed in a square region measuring 800m × 800m. The signal propagation model is chosen to include the log-normal shadowing effect, which introduces random fluctuation of the received signal power according to a log-normal distribution. Figure 4 illustrates the tradeoff between distance and packet loss ratio over a single link in the network, for the receiver power thresholds of data communication and carrier sense, respectively. The wireless nodes simulate the IEEE 802.11 protocol for medium access control.

The *Foreman CIF* sequence is encoded with an MPEG-2 encoder. Different video descriptions are generated by fixing the source coding rate for the main (systematic) description at 1.0 Mbps for SLEP, while varying the rates of Wyner-Ziv descriptions in conjunction with different (n, k) parameters of the RS code.

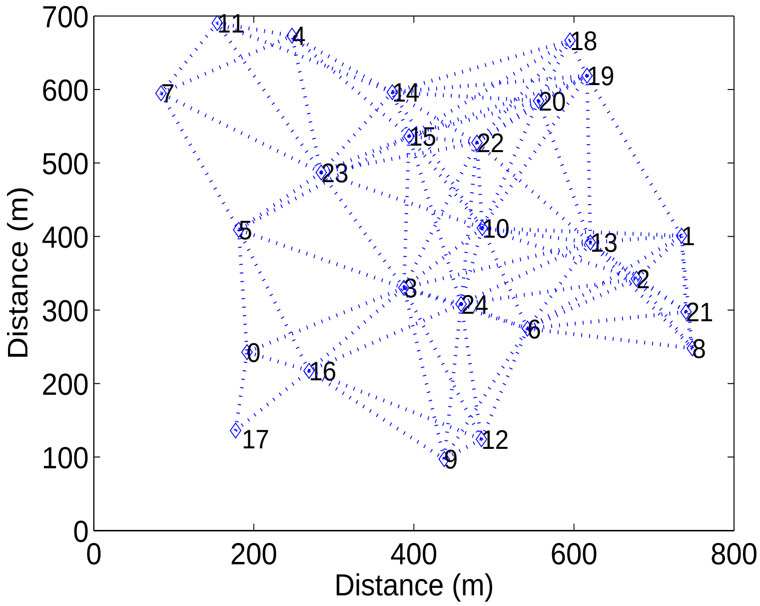

Figure 3. A network consisting of 25 nodes in a 800m-by-800m square. For the chosen set of parameters in the propagation model, nodes within 250m can communicate with a packet loss ratio of 3%.

5.1. Description Selection

We first compare the performance of SLEP and FEC in the network as shown in Fig. 3. Link quality variation is caused by node mobility. For SLEP, the source coding rate of the main (systematic) description is 1.0 Mbps. The Wyner-Ziv description is chosen from a number of available candidates encoded at 1 Mbps, 500 Kbps, 400 Kbps and 337 Kbps, with a RS code having parameters (19,16), (22, 16), (23, 16) and (24, 16) respectively. For FEC, the available candidates have source coding rates of 1 Mbps, 800 Kbps, 700 Kbps, 600 Kbps and 500 Kbps, with RS codes having parameters (19,16), (18,12), (21,12), (24,12), and (19,6) respectively. The parameters for different FEC and SLEP descriptions are listed in Tables 2 and 3. The receiver performs online estimation of end-to-end packet loss ratio as explained in Section 4.1 and feeds back this information to the sender. The sender then calculates the expected distortion associated with each description using the model derived in Section 4.2, and chooses the one yielding the lowest expected end-to-end distortion. Figure 5 illustrates the selected best SLEP description corresponding to different packet loss ratios. Over a period of 50 seconds, Fig. 6 shows that as the estimated packet loss ratio changes, a different Wyner-Ziv description is selected to trade off error-resilience with received video quality. The same experiment is carried out with the FEC candidate descriptions from Table. 2, and the resulting frame PSNRs of SLEP and FEC are compared

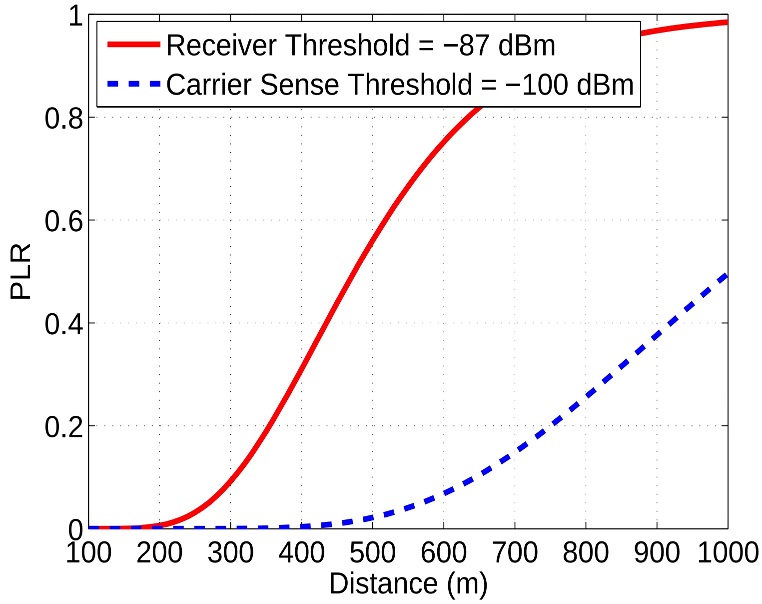

Figure 4. Packet loss ratio versus distance over a single link with the log-normal shadowing propagation model. Results for both the receiver and the carrier sense range are shown. Following the typical configurations of WLAN cards, we set the carrier frequency at 2.4GHz, the transmitter power at 15 dBm, the receiver power threshold at -87 dBm, and the carrier sense threshold at -100 dBm.

in the bottom plot in Fig. 6. The average PSNR for SLEP during this period is 32.7 dB, whereas that of FEC is 30.6 dB. We also note from the PSNR traces in Fig. 6 that SLEP can sustain the video quality more gracefully by replacing the lost portions of the video signal by the coarsely quantized Wyner-Ziv descriptions, whereas FEC suffers from more frequent and drastic quality drops resulting from the failure of RS decoding.

Table 2. Candidate descriptions for FEC.

Description ID	Main desc. rate	(n,k) in RS code	Total rate
FEC0	1.0 Mbps	(19, 16)	1.27 Mbps
FEC1	800 Kbps	(18, 12)	1.35 Mbps
FEC2	700 Kbps	(21, 12)	1.39 Mbps
FEC3	600 Kbps	(24, 12)	1.43 Mbps
FEC4	500 Kbps	(19, 6)	1.49 Mbps

Table 3. Candidate Wyner-Ziv descriptions for SLEP.

Description ID	Main desc. rate	WZ desc. rate	(n,k) in RS Slepian-Wolf code	Total rate
SLEP0	1.0 Mbps	1.0 Mbps	(19, 16)	1.27 Mbps
SLEP1	1.0 Mbps	500 Kbps	(22, 16)	1.30 Mbps
SLEP2	1.0 Mbps	400 Kbps	(23, 16)	1.32 Mbps
SLEP3	1.0 Mbps	337 Kbps	(24, 16)	1.32 Mbps

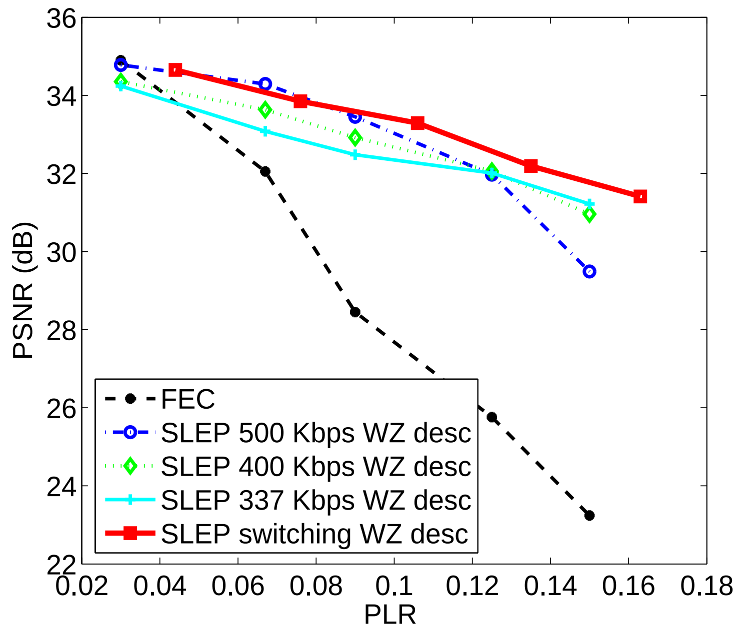

Figure 5. Decoded video PSNR versus PLR. Switching the Wyner-Ziv description according to the PLR results in the best decoded video quality.

5.2. Path Selection

When multiple paths are available from source to destination, it is usually not straightforward to know which candidate path will lead to the best end-to-end performance. For instance, in the network depicted by Fig. 3, several 2-hop or 3-hop paths can be determined from source Node 4 to destination Node 8. Whereas a path with shorter hop can support a higher available bandwidth, as it introduces less contention of traffic, it also suffers from higher packet loss ratio due to the longer distance in each hop. On the other hand, the paths containing 3 hops offer lower available bandwidth but more reliable transmission over each hop.

Using the video distortion model to predict the end-to-end performance of each candidate description over the path with estimated packet loss ratio and available bandwidth, one can choose the most appropriate description for each path, and then compare the paths in terms of the best-achievable end-to-end performance.

Figures 7 and 8 show received video quality both from the model and from actual network simulation and decoding. Note that the trends in the relative performance of the different descriptions are captured by the model. By comparing the best achievable PSNR from the two candidate paths, one chooses the 3-hop path as the preferred route. This comparison is summarized in Table 4.

Table 4. Comparison between two alternative paths for video streaming in an ad hoc wireless network

Quantity	2-hop path	3-hop path
Available Rate	1.5 Mbps	1.2 Mbps
Packet loss ratio	9.2%	4.0%
Chosen source rate of the Wyner-Ziv description	1.0 Mbps (Desc #0)	500 Kbps (Desc #1)
Chosen transmitted Wyner-Ziv bit-rate	420 Kbps	138 Kbps
PSNR predicted by model	34.0 dB (worse path)	34.3 dB (better path)
PSNR observed in network experiment	33.5 dB (worse path)	34.2 dB (better path)

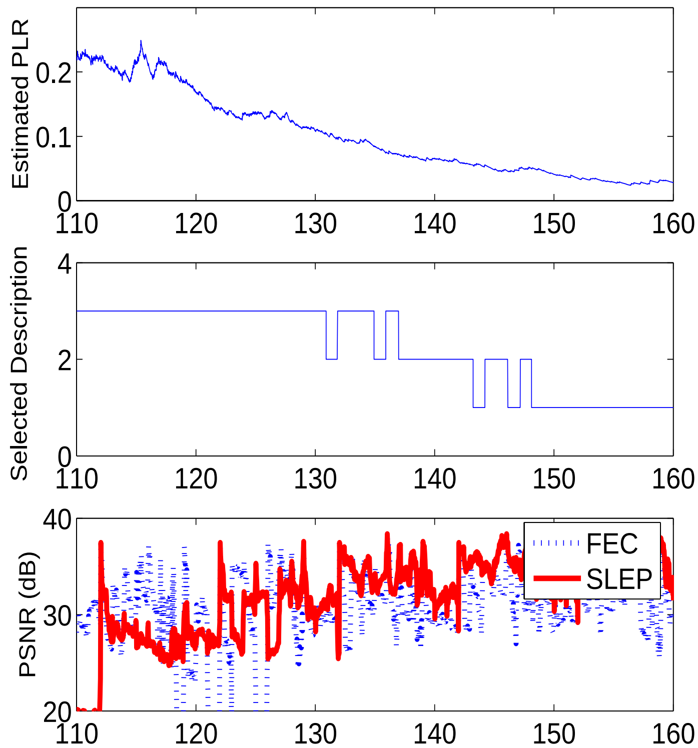

Figure 6. Estimated packet loss rate (top), chosen Wyner-Ziv video description (middle) and decoded video quality using SLEP versus FEC (bottom). Referring to Table. 3, description number 0 in the middle plot stands for the Wyner-Ziv description with rate 1 Mbps, 1 for that with rate 500 Kbps, 2 for that with 400 Kbps, and so on. Switching the SLEP descriptions gives better video quality with smaller fluctuations than switching FEC descriptions.

6. CONCLUSIONS

Unlike conventional FEC, where video quality drops dramatically once the observed packet loss ratio exceeds the protection capability of the selected RS code, the proposed SLEP scheme yields graceful degradation in the video quality over a range of packet loss rates. Thus, over the ad hoc wireless network, when packet loss ratio fluctuates over time, the proposed SLEP yields superior video quality compared to FEC. When multiple paths are available for transmission, with different bit-rates, different packet loss ratios and different number of hops, it is not always straightforward to transmit on the path with the highest bandwidth or the lowest packet loss ratio or the fewest number of hops. Using a video distortion model for SLEP, we show that it is possible to select the best path among the available alternatives.

ACKNOWLEDGMENTS

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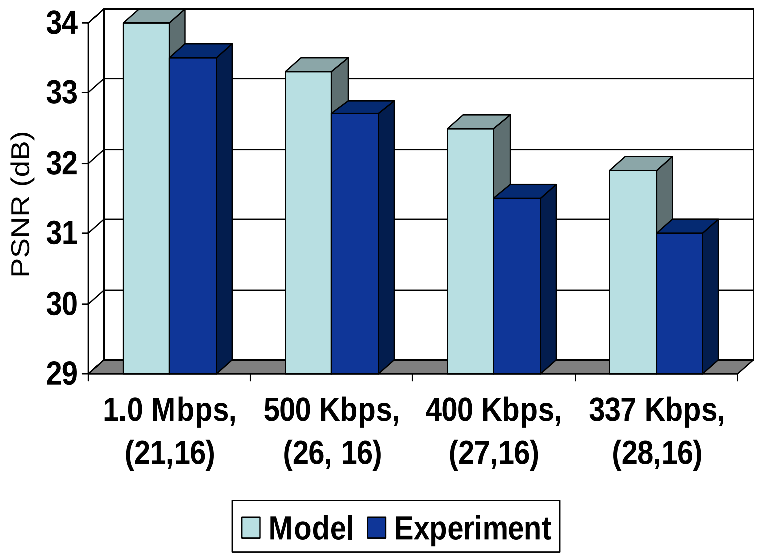

Figure 7. Estimated and observed decoded video PSNR using various descriptions over the 2-hop path (4-10-8), with available bandwidth of 1.5 Mbps and packet loss ratio around 9.0%. The best Wyner-Ziv description is SLEP0 (@ rate 1 Mbps), with RS parameters (21,16). This results in a transmitted Wyner-Ziv bit-rate of 420 Kbps. Since the main (systematic) description was also encoded at 1 Mbps, it turns out that the best performing Wyner-Ziv description is equivalent to the FEC case for the 2-hop path.

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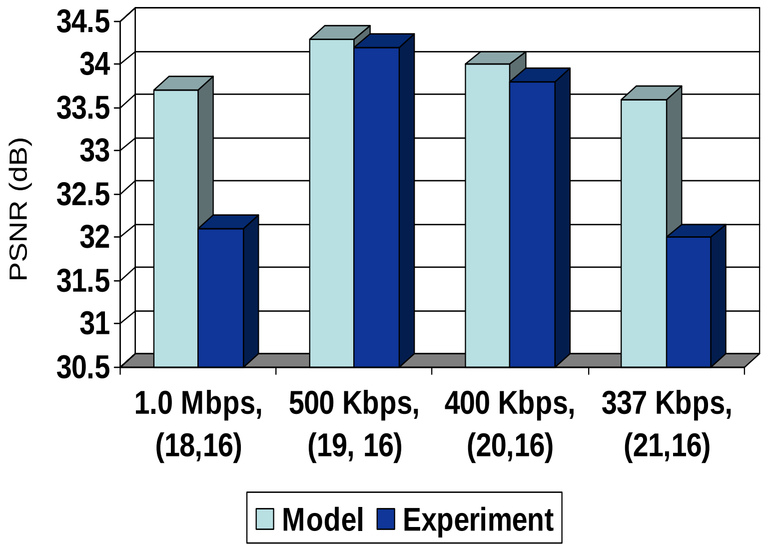

Figure 8. Estimated and observed decoded video PSNR using various descriptions over the 3-hop path (4-15-10-8), with available bandwidth of 1.2Mbps and packet loss ratio around 4.0%. The best Wyner-Ziv description is SLEP1 (@ rate 500 Kbps), with RS parameters (19,16). This results in a transmitted Wyner-Ziv bit-rate of 138 Kbps. Since the main (systematic) description was encoded at 1 Mbps, it turns out that SLEP is better than conventional FEC for the 3-hop path.

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