Distortion Optimal Transmission of Multi-Layered FGS Video over Wireless Channels

Negar Nejati, Homayoun Yousefi'zadeh, *Sr. Member IEEE*, and Hamid Jafarkhani, *Fellow IEEE*

***Abstract*— We identify an analytical expression for the distortion of a scalable video bitstream containing a Base Layer (BL) and one or more Enhancement Layer (EL) bitstreams. Considering the different priority of BL and EL, we adopt our distortion expression for each of these bitstreams separately. Utilizing these distortion models, we propose a pair of low complexity Unequal Error Protection (UEP) methods for transmitting these bitstreams over a tandem channel. These one-dimensional Forward Error Correction (FEC) coding schemes, protect each bitstream against both bit errors caused by fading and packet erasures caused by network buffering. They also combat temporally correlated loss effects observed over tandem channels by using optimal symbol interleaving. We evaluate the performance of our proposed schemes by comparing their results against those of Equal Error Protection (EEP) and those of a number of UEP methods as well. We illustrate the performance advantage of our schemes over other schemes for different available budgets and channel conditions.**

I. Introduction

In the past decade, there have been great improvement in multimedia streaming techniques over wireless channels. Despite all these improvements, many challenges still exist in providing an acceptable level of Quality of Service (QoS) for these applications.

A. Prior Work

As an integral part of multimedia streaming, UEP techniques have been broadly used to protect a video bitstream according to the priority of the different levels of that bitstream. The broad use of UEP techniques requires allocating system resources in order to minimize the expected distortion of a bitstream delivered over a transmission medium. In [1], a combination of Fine Granularity Scalability (FGS), also known as progressiveness, and UEP techniques is proposed. Other UEP techniques such as those proposed in [2], [3], and [4] protect different types of frames, i.e., Intra-coded picture (I), Predicted picture (P), and Bi-predictive picture (B) frames in a video sequence according to their importance. In [5], a two-level UEP technique is proposed that considers frame priorities as well as layer priorities of scalable coded video transmitted over packet erasure channels. The works of [6] and [7] propose frameworks of multimedia transmission over packet erasure channels.

Wireless channels are identified by temporally correlated tandem loss patterns which appear in the form of bit errors related to fading effects and packet erasures related to network layer buffering. While, the effects of fading related bit errors is not considered in any of the literature works above, some other works have considered the problem of transmitting a video stream over a tandem channel. In [8], Reed-Solomon (RS) codes are used at the transport layer for unequal inter-packet protection and Rate-Compatible Punctured Convolutional (RCPC) codes are used at the link layer to provide unequal intra-packet protection. Both [9] and [10] use RCPC, Cyclic Redundancy Check (CRC), and RS product codes for scalable multimedia transmission over wireless tandem channels. Several other algorithms are introduced in [11] for progressive image transmission. Those algorithms all use product codes which are complex and time consuming in nature.

B. Contributions

In this paper, we propose a novel, low complexity UEP scheme for transmitting a scalable video sequence over a tandem channel. Specifically, the contributions of this paper are as follows:
1. We propose a simple yet accurate analytical expression capable of capturing the expected distortion of a scalable video bitstream transmitted over a wireless tandem channel.
2. Utilizing this expression and considering channel conditions, we propose an efficient algorithm for allocating the available transmission budget between the BL and EL bitstreams of a video sequence such that the distortion of the received video is minimized.
3. Having identified the BL budget, we propose a method for allocating the budget among the Group of Pictures (GOPs) of the BL bitstream based on the contribution of each GOP to the distortion of the BL.
4. We formulate and solve a distortion-optimal problem to distribute the allocated budget of each GOP of the BL bitstream among the frames of that GOP based on frame impact on the distortion of GOP.
5. Finally, we address the problem of optimally allocating the budget to progressive EL bitstreams resulting in minimizing the distortion of the sequence.

The video codec used in this work is MoMuSys [12] [13] implementing MPEG4 standard with FGS functionality. We note that while using the FGS feature reduces the quality of the decoded video compared to that of a single layer video [14], it can improve the quality of reconstructed video transmitted over a tandem channel. This is due to the fact that this feature allows for decoding a received truncated EL bitstream in conjunction with a BL bitstream potentially reducing the effects of bit errors [15], [16], [17]. In addition, the FGS feature reduces the error propagation effects through the EL of the other frames because the EL bitstream of each frame is decoded independently from the EL of previously decoded frames of the GOP to which it belongs.

 The authors are with the Department of EECS, University of California, Irvine, email [nnejati,hyousefi,hamidj]@uci.edu. This work appears in part in proceedings of IEEE DCC'08 and IEEE DCC'09 and is sponsored by a research contract from the Boeing Company.

The rest of this paper is organized as follows. In Section II, we briefly introduce the underlying channel model capturing both bit errors and packet erasures. A discussion pertaining to the derivation of an analytical distortion model for a scalable video bitstream is provided in Section III. In Section IV, we formulate and solve a pair of distortion-optimal problems associated with the BL and EL of a video sequence, using the proposed distortion model. In Section V, we provide our numerical comparison results. The conclusions of this paper are presented in Section VI.

II. Channel Model

As indicated earlier, both packet erasures and bit errors need to be captured in order to properly model a packetized wireless channel. While bit errors are produced by the wireless transmission medium, packet loss is caused by network impairments such as congestion. To capture the effects of bit errors and packet erasures in our study, we have respectively used a two state Gilbert-Elliott (GE) Markov chain and another independent Gilbert (G) Markov chain [18]. Bit errors caused by a fading channel are modeled by the two state GE chain where γ is the self transitioning probability for GOOD state and similarly β is the probability of self transitioning for BAD state. Each state is also associated with an error probability. In the GE model, the probability of having n errors in k transmissions is calculated as:

$$\mathcal{P}(n,k) = \mathcal{P}(n,k,\mathcal{G}) + \mathcal{P}(n,k,\mathcal{B}), \tag{1}$$

where $\mathcal{P}(n,k,\mathcal{G})$ and $\mathcal{P}(n,k,\mathcal{B})$ are the probabilities of having n errors in k transmissions and ending up in GOOD and BAD state, respectively. These probabilities are calculated as:

$$\begin{aligned}\mathcal{P}(n,k,\mathcal{G}) =& (1-\epsilon_{\mathcal{G}})[\gamma\mathcal{P}(n,k-1,\mathcal{G}) + (1-\beta)\mathcal{P}(n,k-1,\mathcal{B})] \quad (2)\\ &+ \epsilon_{\mathcal{G}}[\gamma\mathcal{P}(n-1,k-1,\mathcal{G}) + (1-\beta)\mathcal{P}(n-1,k-1,\mathcal{B})],\\ \mathcal{P}(n,k,\mathcal{B}) =& (1-\epsilon_{\mathcal{B}})[(1-\gamma)\mathcal{P}(n,k-1,\mathcal{G}) + \beta\mathcal{P}(n,k-1,\mathcal{B})] \quad (3)\\ &+ \epsilon_{\mathcal{B}}[(1-\gamma)\mathcal{P}(n-1,k-1,\mathcal{G}) + \beta\mathcal{P}(n-1,k-1,\mathcal{B})],\end{aligned}$$

where $\mathcal{P}(n,0,\mathcal{G}) = \mathcal{P}(n,0,\mathcal{B}) = 0$ for $n \neq 0$ and the initial conditions are expressed as:

$$\mathcal{P}(0,0,\mathcal{G}) = \frac{1-\beta}{2-\gamma-\beta}, \mathcal{P}(0,0,\mathcal{B}) = \frac{1-\gamma}{2-\gamma-\beta},$$

The probability of symbol error for the GE chain depends on the average received Signal-to-Noise Ratio (SNR), the modulation scheme, the number of signal points in the modulation constellation M, the number of transmit/receive antennas, and the utilized coding technique. It is shown in [19] that for a channel utilizing Maximum Ratio Combining (MRC) with a single transmit and R_a receive antennas, the probability of the symbol error in GOOD state is calculated as follows:

$$\begin{aligned}\epsilon_{\mathcal{G}} =& \tfrac{M-1}{M} - \tfrac{1}{\pi}\sqrt{\tfrac{\vartheta_{\mathcal{G}}}{1+\vartheta_{\mathcal{G}}}}\{(\tfrac{\pi}{2} + \tan^{-1}\xi_{\mathcal{G}})\textstyle\sum_{j=0}^{R_a-1}\binom{2j}{j}\tfrac{1}{[4(1+\vartheta_{\mathcal{G}})]^j}\\ &+ \sin(\tan^{-1}\xi_{\mathcal{G}})\textstyle\sum_{j=1}^{R_a-1}\sum_{i=1}^{j}\tfrac{\sigma_{ij}}{(1+\vartheta_{\mathcal{G}})^j}[\cos(\tan^{-1}\xi_{\mathcal{G}})]^{2(j-i)+1}\},\end{aligned} \tag{4}$$

where $\vartheta_{\mathcal{G}} = SNR_{\mathcal{G}}\sin^2(\frac{\pi}{M})$, $\xi_{\mathcal{G}} = \sqrt{\frac{\vartheta_{\mathcal{G}}}{1+\vartheta_{\mathcal{G}}}}\cot\frac{\pi}{M}$, and $\sigma_{ij} = \frac{\binom{2j}{j}}{\binom{2(j-i)}{j-i}4^i[2(j-i)+1]}$. Similarly, the probability of symbol error for BAD state $\epsilon_{\mathcal{B}}$ is calculated by replacing $SNR_{\mathcal{G}}$, $\xi_{\mathcal{G}}$, and $\vartheta_{\mathcal{G}}$ with their counter parts in BAD state. Further, per state probabilities of error for GOOD and BAD states can be calculated by properly scaling the values of SNR in the equation above when utilizing multiple transmit antenna Space-Time Block Codes (STBC).

We model packet erasures with a G chain. The G chain operates similar to the GE chain with $\epsilon_{\mathcal{G}} = 0$ and $\epsilon_{\mathcal{B}} = 1$. However, we note that the probabilities of error are related to network buffering dynamics as opposed to fading statistics [20] [21]. The average probability of packet erasure to which we refer as $\mathcal{P}_{ers}$ depends on $\mathcal{P}_e = \frac{1-\gamma}{2-\gamma-\beta}$, the average probability of a symbol erasure. We can see that increasing β will increase $\mathcal{P}_e$ and consequently the probability of packet erasure.

III. Proposed Analytical Distortion Expression

In this section, we propose an analytical distortion model for a scalable video bitstream. The video bitstream is encoded using the FGS option and contains a BL and one or more ELs. Basic video quality is guaranteed by receiving BL bitstream and can be improved by adding the contents of EL bitstreams to it. It is important to note that receiving error free intra-coded frames can prevent the propagation of error into the rest of the sequence. We assume that by providing sufficient error protection to the intra-coded frames, GOPs can be treated independently. Therefore, the expected distortion of the sequence is calculated as the summation of the expected distortion of all GOPs of the sequence as:

$$\varepsilon_D^{Seq} = \sum_{i=1}^{N_{GOP}} \varepsilon_D^{GOP}(i) \tag{5}$$

where N_{GOP} is the number of GOPs in the sequence and $\varepsilon_D^{GOP}(i)$ represents the expected distortion of the i-th GOP of the video sequence. The expected distortion of a GOP is represented using Table I in which it is assumed that the probability of receiving an I frame is not less than a given threshold, θ. As it was explained before, we have captured the expected distortion of the whole sequence assuming that the distortion of GOPs are independent from each other. The accuracy of this assumption depends on θ, which is calculated in the process of evaluating an accurate distortion model, capturing the experimental results of MoMuSys codec for the same channel conditions. In Table I, each row indicates the pattern of the received frames in the GOP at the BL bitstream and also the distortion of reconstructed GOP associated with this pattern after using the Error Concealment (EC) technique. Assuming n is the size of GOP excluding the I frame, the total number of rows is 2^n. The first row indicates the case in which all the n frames are lost and the last row shows the case in which all the n frames of the GOP are received correctly. In Table I, $\varepsilon_D^{ROW}(i)$ indicates the distortion of GOP associated with the i-th row and $\mathcal{P}_{BL}(1,j)$ is the probability of receiving BL of frame j without error. $\mathcal{P}_{BL}(1,j)$

TABLE I
THE DISTORTION OF A GOP OF A SCALABLE BITSTREAM BASED ON THE PATTERN OF RECEIVED FRAMES AT THE BL BITSTREAM

Frame 1	Frame 2	...	Frame n	Distortion
$\mathcal{P}_{BL}(0,1)$	$\mathcal{P}_{BL}(0,2)$	...	$\mathcal{P}_{BL}(0,n)$	$\varepsilon_D^{ROW}(0)$
$\mathcal{P}_{BL}(0,1)$	$\mathcal{P}_{BL}(0,2)$	...	$\mathcal{P}_{BL}(1,n)$	$\varepsilon_D^{ROW}(1)$
			...	
$\mathcal{P}_{BL}(1,1)$	$\mathcal{P}_{BL}(1,2)$	...	$\mathcal{P}_{BL}(1,n)$	$\varepsilon_D^{ROW}(2^n-1)$

is identified as:

$$\mathcal{P}_{BL}(1,j) = \prod_{k=0}^{N_{pck}^{j}-1} \mathcal{P}_{pck}(1,k) \tag{6}$$

where N_{pck}^{j} defines the number of packets for transmitting BL of frame j and $\mathcal{P}_{pck}(1,k)$ represents the probability of receiving the k-th packet of the BL of frame j free of error. $\mathcal{P}_{pck}(1,k)$ is calculated as: $\mathcal{P}_{pck}(1,k) = (1-\mathcal{P}_{es})^{L}$ where L is the number of symbols in each packet. As a matter of convenience and without losing generality, we assume that each symbol is one byte long and $\mathcal{P}_{es}$ is the probability of symbol error. For channels with memory, $\mathcal{P}_{es} = 1 - \mathcal{P}(0,s)$ where s is the symbol size. Further, $\mathcal{P}(n,k)$ is the probability of having n bits in error out of k transmitted bits as calculated by (1). $\mathcal{P}_{BL}(0,j) = 1 - \mathcal{P}_{BL}(1,j)$ is the probability of loss for BL of frame j. We use $\mathcal{P}^{k,j}$ to refer to the probability of the j-th frame in the k-th row of Table I. We note that $\mathcal{P}^{k,j}$ is either $\mathcal{P}_{BL}(0,j)$ or $\mathcal{P}_{BL}(1,j)$ depending on the loss pattern of row k in the probability table of that GOP. Using the table, the expected distortion of GOP i can be defined as follows:

$$\varepsilon_{D}^{GOP}(i) = \sum_{k=0}^{2^{n}-1} \varepsilon_{D}^{ROW}(k) \tag{7}$$

$$\varepsilon_{D}^{ROW}(k) = \prod_{j=1}^{n} \mathcal{P}^{k,j} d_{BL}^{GOP}(k) - d_{EL}^{GOP}(k) \tag{8}$$

where $\varepsilon_{D}^{ROW}(k)$ is the expected distortion of the GOP associated with the k-th row of the table. This distortion is defined in (8) where $d_{BL}^{GOP}(k)$ is the distortion of the BL of the GOP associated with the k-th row and $d_{EL}^{GOP}(k)$ is the improvement in GOP's distortion as the result of decoding the EL. $d_{EL}^{GOP}(k)$ is calculated considering two facts. First, the EL bitstream of each frame can be decoded and therefore improve the distortion of that frame only if the BL bitstream of that frame is received correctly. Second, decoding of the EL bitstream of each frame is independent of the previously decoded EL frames of the same GOP. Considering the probability of receiving the BL bitstream of the GOP frames, one can express $d_{EL}^{GOP}(k)$ as:

$$d_{EL}^{GOP}(k) = \sum_{j=0}^{n} \mathcal{P}^{k,j} d_{EL}^{Frame}(j) \tag{9}$$

where $d_{EL}^{Frame}(j)$ is the improvement in the expected distortion of j-th frame of that GOP when the BL of that frame is received. Since the EL bitstream of each frame is encoded progressively, this distortion depends on the position of the first bit error in that frame which can be subsequently defined as:

$$d_{EL}^{Frame} = \sum_{i=1}^{E+1} D_{i-1}\mathcal{P}_{es}(1-\mathcal{P}_{es})^{(i-1)} \tag{10}$$

In Equation (10), E is the length of EL bitstream for the current frame, D_i is the improvement in the distortion of the current decoded frame when the first i bytes of the EL bitstream are received error free, and $\mathcal{P}_{es}$ is the probability of a symbol error, calculated by (1). To verify our proposed model, we encode a large number of qcif sequences into two- or three-layer bitstreams using MoMuSys codec. From among the set of experiments performed, we report our results for Miss-America sequence encoded into two layers and Foreman sequence encoded into three layers [17]. In the case of Miss-America sequence, the rate of BL and FGS are set as 25fps. In the case of Foreman sequence, the rate of BL and FGS bitstreams are set as 10fps each while adding the FGST bitstream increases the overall rate to 30fps. For our reported results, the size of GOP is 4 and the encoded bit rate of Miss-America sequence is 288 kbps while the bit rate of Foreman sequence is 768 kbps. Utilizing two different threshold values, Fig. 1 compares sample results of the proposed analytical model with the experimental distortion results of Miss-America sequence under different channel conditions. Fig. 1(c) shows the same results for Foreman sequence with a threshold of 0.994. As shown in the Fig. 1(b), the analytical model cannot closely match the experimental results for lower threshold values, specially, in the case of channels identified with high error rates. We note that the latter is due to the fact that the GOPs independence assumption is no longer valid in such cases. Albeit sample results are reported for Miss-America and Foreman sequences, we note that similar patterns are observed in the case of other sequences.

IV. Distortion Optimized Methods

In this section, we propose two distortion-optimal methods of protecting and transmitting scalable video bitstreams over a tandem channel utilizing the proposed analytical distortion model of Section III. In Section IV-A, we describe a method for allocating the total transmission budget between BL and EL bitstreams based on channel conditions and the performance of the codec. We formulate and solve a pair of distortion-optimal rate allocation problems for a single layer BL bitstream and a progressive EL bitstream in Section IV-B and IV-C, respectively.

A. Budget Allocation

Fig. 2 shows the performance of the codec for Miss-America and Foreman sequences under different channel conditions. As decoding of the EL bitstreams of each frame depends on receiving the BL bitstream of that frame, our budget allocation strategy between BL and ELs bitstreams depends on the probability of receiving BL bitstream, $\mathcal{P}_{Rec}(BL)$. This probability depends on the length of BL of each frame and $\mathcal{P}_{es}$ and consequently to $SNR_{\mathcal{G}}$ (1-4). Therefore for different sequences with different frame sizes, the channel conditions may be represented by different regions of $SNR_{\mathcal{G}}$. Denoting L_{BL}, L_{EL}, and L_{Trans} as the data size of BL bitstream, EL bitstreams, and the total transmission budget with $L_{Trans} \geq (L_{BL} + L_{EL})$, Table II illustrates our proposed budget allocation strategy to the BL and EL bitstreams for three channel conditions. In a poor channel condition, $\mathcal{P}_{Rec}(BL)$ is less than 0.0675. This probability is calculated considering the performance of the codec in Fig. 2 using Equations (6) and (1-4). As illustrated by Fig. 2(a) and (b), channel parameter of $SNR_{\mathcal{G}} \leq 15$ and $SNR_{\mathcal{G}} \leq 25$ represent a poor channel condition for Miss-America and Foreman sequences, respectively. As shown in the table, we use the total available budget to protect the BL under poor channel conditions since receiving the EL without the BL is useless. A fair channel condition is the case that $\mathcal{P}_{Rec}(BL)$ is greater than 0.0675 and less than 0.9107. In this case the BL of some frames may receive correctly at the decoder. Therefore we first allocate an amount of parity to the BL that can guarantee

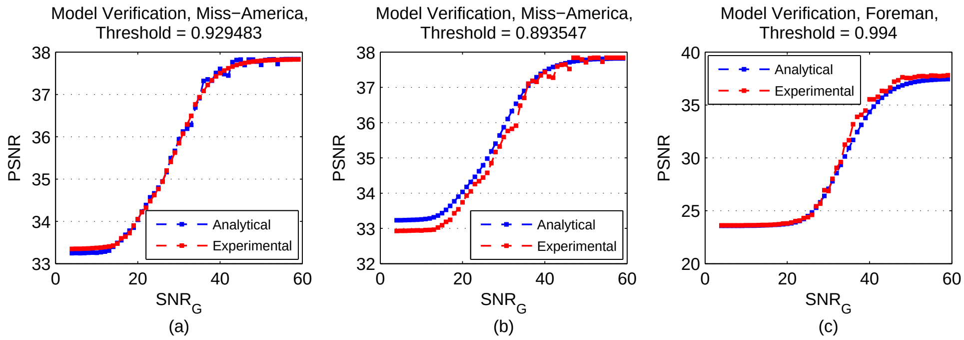

Fig. 1. A comparison of analytical and experimental distortion results of Miss-America sequence with a threshold value of (a) 0.929483 and (b) 0.893547 and (c) a verification results of Foreman sequence with a threshold value of 0.994.

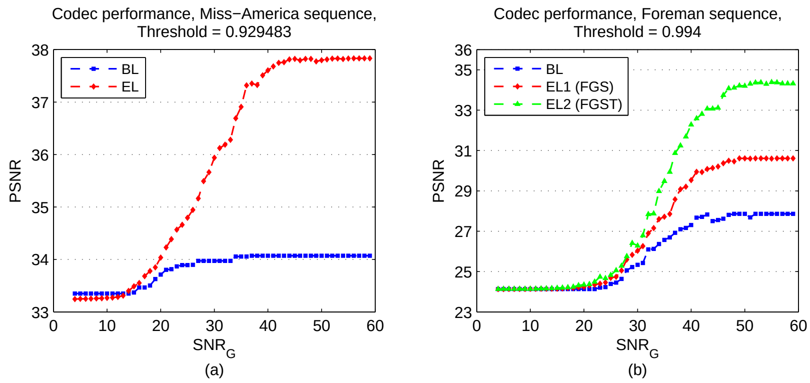

Fig. 2. The codec performance for BL and BL+ELs bitstreams under different channel conditions for (a) Miss-America Sequence with one EL bitstream and (b) Foreman sequence with two EL layers.

TABLE II

THE BUDGET ALLOCATION STRATEGY UNDER DIFFERENT CHANNEL CONDITIONS

		BL Budget		
$\mathcal{P}_{Rec}(BL)$	Condition	Data	Parity	EL Budget
≤ 0.0675	Poor	L_{BL}	$L_{Trans} - L_{BL}$	0
$[0.0675 - 0.9107]$	Fair	L_{BL}	$0.5L_{BL}$	$L_{Trans} - 1.5L_{BL}$
≥ 0.9107	Good	L_{BL}	$0.05L_{BL}$	$L_{Trans} - 1.05L_{BL}$

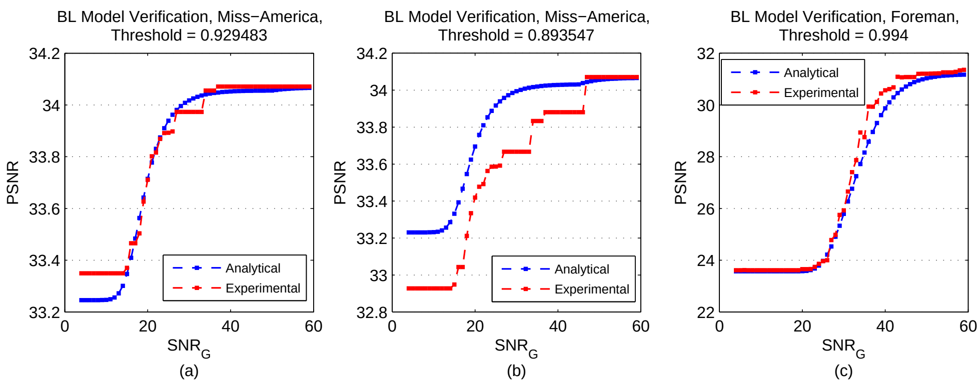

Fig. 3. A comparison of analytical and experimental distortion results of Miss-America sequence with a threshold value of (a) 0.929483 and (b) 0.893547 and (c) a verification result of Foreman sequence with a threshold value of 0.994.

its error free delivery and next assign the remaining budget to the EL. Our experiments for different sequences show that in the worst case, a parity budget equal to 50% of the original BL bitstream size can protect the BL for fair channel conditions. In Fig. 2(a) and (b), $15 \leq SNR_{\mathcal{G}} \leq 30$ and $25 \leq SNR_{\mathcal{G}} \leq 40$ show the codec performance in a fair channel condition for Miss-America and Foreman sequences, respectively. Finally, the good channel condition is when $\mathcal{P}_{Rec}(BL)$ is greater than 0.9107. Fig. 2(a), where $SNR_{\mathcal{G}}$ is greater than 30 represents the performance of the codec in this channel condition for Miss-America sequence and Fig. 2(b), $SNR_{\mathcal{G}} \geq 40$, shows the same results for Foreman sequence. As BL is delivered almost free of error in this case, more budget can be assigned to the EL bitstreams to improve the sequence quality. In this case, we allocate a parity budget equal to 5% of the size of the BL and allocate the rest of the budget to the EL bitstream.

B. Single Layer Bitstream

In this subsection, we formulate our optimization problem for a single BL bitstream. Our goal is to minimize distortion of the transmitted video over a tandem channel by optimally allocating the available transmission budget to the frames of an encoded sequence based on the importance of frames in the quality of the sequence. This subsection introduces the analytical model of distortion and defines two alternative transmission schemes along with the optimization problem technique.

1) Modified Expected Distortion Model: In Section III, we provided a general distortion model for a scalable video bitstream. We note that our general distortion model can be adopted for the case of a single layer bitstream by ignoring d_{EL}^{GOP} in Equation (8). Therefore, the expected distortion of a GOP for single layer bitstream can be defined as follows:

$$\varepsilon_D^{GOP}(i) = \sum_{k=0}^{2^n-1} \prod_{j=1}^{n} \mathcal{P}^{k,j} d_{BL}^{GOP}(k) \tag{11}$$

We note that the probability of receiving frame j with no error, $\mathcal{P}_{BL}(1, j)$, can be calculated using (6). Further the distortion of the BL of the current GOP in row i, $d_{BL}^{GOP}(i)$, is calculated off-line based on the bitstream, codec, and EC performance.

Next, we verify the accuracy of our model. Again from among the set of experiments performed, we report our results for Miss-America and Foreman sequences encoded according to the discussion of Section III. Using two different threshold values, Fig. 3(a) and (b) compare sample results of our proposed analytical model with experimental distortion results of Miss-America sequence under different channel conditions. Fig. 3(c) shows the accuracy of the model for the Foreman sequence with a threshold value of 0.994. As shown in Fig. 3(a) and (c), if the probability of receiving I frames are greater than a given threshold, the assumption of independency of distortion of GOPs is relatively accurate. In this case the overall minimum expected distortion for the whole bitstream can be achieved by minimizing the expected distortion of each GOP, separately. We note that each frame in a GOP has a different effect on the distortion of the GOP depending on its encoding type and location in the GOP. The latter constitutes a rate allocation problem that may be solved optimally.

2) Distortion-Optimal Transmission: We now discuss three alternatives of protecting a video bitstream against channel loss effects including two optimization techniques capturing the rate allocation problem described above.

The first alternative used as the baseline, is the so-called Equal Length Protection (ELP) technique. In this technique, the total parity budget is distributed equally among all the inter-coded frames. In other words, the amount of parity allocated to each frame is calculated independent of the length of that frame and the effect of that frame on the total distortion of the GOP. In ELP, the packet length is fixed and set equal to the length of the RS codeword. This one dimensional code protects each packet against the bit errors with a fix number of parities and cannot support the packets against packet erasures.

As the second alternative, we introduce a simple linear rate allocation technique based on the distortion caused by the loss of each GOP and each frame. We refer to such technique as Linear Distortion Optimal (LDO) technique. As mentioned previously, the loss of frames with different types and at different locations have different effects on the distortion of their GOP. LDO is a simple linear rate allocation technique for transmitting the encoded video bitstream over a tandem channel. LDO assigns the parity budget to each frame based on the impact of the distortion of frame loss on the total distortion of that GOP. This rate allocation can be formulated as follows:

$$Budget_{frame}(i_j) = Budget_{GOP}(i) \times \frac{dist_{frame}(i_j)}{dist_{GOP}(i)} \tag{12}$$

$$dist_{GOP}(i) = \sum_{j=0}^{n_i-1} dist_{frame}(i_j), \tag{13}$$

where $Budget_{frame}(i_j)$ represents the budget of frame j in GOP i, $dist_{frame}(i_j)$ is the distortion of GOP i when frame j of the GOP is lost, $dist_{GOP}(i)$ is the average GOP distortion caused by any single frame lost, and n_i is the size of GOP i, excluding the I frame. The budget of GOP i can also be calculated utilizing the same approach as:

$$Budget_{GOP}(i) = total\_Budget \times \frac{dist_{GOP}(i)}{total\_Dist}, \tag{14}$$

$$total\_Dist = \sum_{i=0}^{N_{GOP}-1} dist_{GOP}(i), \tag{15}$$

where N_{GOP} is the number of GOPs in the whole video sequence, $total\_Budget$ is the maximum transmission budget depending on the available bandwidth, and $total\_Dist$ is the average sequence distortion caused by any single GOP lost. To implement this technique, we calculate required distortions offline by inserting an error manually into the specific location of the encoded bitstream, decoding the new bitstream, and calculating its distortion.

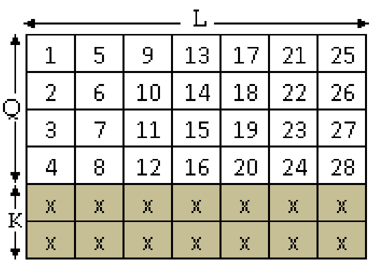

Fig. 4. An illustration of the proposed OSL technique.

Finally, we formulate our constrained optimization problem to which we refer to as Optimal Single Layer (OSL). We reiterate that the OSL method is associated with the transmission of video over a channel characterized by tandem loss. As shown in previous sections, the expected distortion of a GOP of a single layer video bitstream can be modeled using (11). We assume that the encoded video bitstream is packetized with a fixed packet size and each frame is protected with a one-dimensional RS code. We note that our coding scheme interleaves the symbols to better cope with the temporally correlated loss observed over the tandem channels of interest. Fig. 4 illustrates our proposed OSL technique. In the figure, L is the fixed packet length, Q is the number of packets containing the data of an encoded video frame, and

K is the number of channel coding symbols in each column. The total budget for transmitting frame l, R_{f_l}, in GOP i is equal to $L * (Q + K)$. The parity budget for intra coded and inter coded frames of each GOP is calculated by taking the following steps:

- Finding the parity budget for the I frame as

$$\mathcal{P}_{rec}(1, I) \geq \theta \tag{16}$$

- Finding the parity budget for the other frames of the GOP as

$$\min_{\mathbf{R_{f_1}}, \mathbf{R_{f_2}}, \ldots, \mathbf{R_{f_n}}} \varepsilon_D^{GOP}(i) \tag{17}$$
$$\text{subject to} : 0 \leq \sum_{l=1}^{n} R_{f_l} < R_T$$

where $\mathcal{P}_{rec}(1, I)$ is the probability of recovery for I frame and θ is the threshold probability of receiving the intra coded frames based on the distortion model. In addition, $\varepsilon_D^{GOP}(i)$ indicates the expected distortion of GOP i in the video sequence and R_{f_l} represents the rate allocated to the l-th frame f_l and consequently the number of parity packets K for that frame. Further, n shows the size of GOP excluding the I frame and R_T is the total number of symbols for transmitting the inter-coded frames of the current GOP. Considering the fact that frames are protected by the RS code in this case, the expected distortion of GOP i in Equation (11), $\varepsilon_D^{GOP}(i)$, will be modified as follows:

$$\varepsilon_D^{GOP}(i) = \sum_{k=0}^{2^n - 1} \prod_{j=1}^{n} \mathcal{P}_{rec}^{k,j} d_{BL}^{GOP}(k) \tag{18}$$

If the j-th frame of the k-th row in the probability table of GOP i is marked as recovered, then $\mathcal{P}_{rec}^{k,j}$ can be represented by $\mathcal{P}_{rec}(1, j)$ which is the probability of recovery for the j-th frame. Otherwise, it would be equal to $\mathcal{P}_{rec}(0, j) = 1 - \mathcal{P}_{rec}(1, j)$. An RS code with K parity symbols can successfully reconstruct the data of each codeword if the number of symbol errors N_{err} and the number of symbol erasures N_{ers} satisfy $2N_{err} + N_{ers} \leq K$. Therefore considering the transmission technique of Fig. 4, $\mathcal{P}_{rec}(1, j)$ can be defined based on $\mathcal{P}_{c_j}$, the probability of recovery of each RS codeword [22] of frame j, as follows:

$$\mathcal{P}_{rec}(1, j) = (\mathcal{P}_{c_j})^L \tag{19}$$

$$\mathcal{P}_{c_j} = \sum_{l=0}^{K_j} \mathcal{P}(N_{err} \leq \lfloor \frac{K_j - l}{2} \rfloor | N_{ers} = l) \mathcal{P}_{ers}(N_j, l), \tag{20}$$

$$\mathcal{P}(N_{err} \leq \lfloor \frac{K_j - l}{2} \rfloor | N_{ers} = l) = \sum_{k=0}^{\lfloor \frac{K_j - l}{2} \rfloor} \mathcal{P}(N_{err} = k | N_{ers} = l), \tag{21}$$

$$\mathcal{P}(N_{err} = k | N_{ers} = l) = \begin{pmatrix} N_j - l \\ k \end{pmatrix} \mathcal{P}_{es}^k (1 - \mathcal{P}_{es})^{N_j - l - k}, \tag{22}$$

where $\mathcal{P}_{es}$ is the probability of symbol error, K_j and Q_j are the number of parity and data symbols for each column of frame j, respectively, and $N_j = Q_j + K_j$ is the number of packets transmitted for that frame. It is important to note that $\mathcal{P}_{rec}(1, j)$ considers the effects of both symbol errors and symbol erasures.

Considering the limitations of the bandwidth for the channel, we assume that the acceptable parity budget for this optimization problem is between 0% to 50%. Under this assumption, this optimization problem can be solved relying on an intelligent search strategy described below. To describe our proposed search strategy, we note that the number of possible allocations can be significantly reduced considering the fact that the earlier frames in GOP have a higher priority. This will add a constraint to our optimization problem as follows:

$$K_0 \geq K_1 \geq K_2 \geq \ldots \geq K_n \tag{23}$$

where K_0 associates with the parity of the I frame, K_i is the number of parity packets allocated to the frame i, and n is the number of the last frame in a GOP. Since I frames are supposed to be received with a probability greater than a threshold, the budget assigned to them will change under different channel conditions. In bad channel conditions, I frames are transmitted with a low rate RS code. However, in a fair or good channel conditions these frames are protected with a higher rate RS code. Hence, we only focus on the parity allocation among the GOP frames other than I frames.

For the case of a GOP size of four, there are three inter-coded frames in the GOP. In this case, the total parity budget for inter-coded frames T, is the summation of K_1, K_2, and K_3. In the case of full search, the number of possible parity packet allocations to the first frame is T and for each case of K_1, the possible parity packet allocations among the second and third frames would be $T - K_1 + 1$. Therefore, the total number of parity packet allocations can be calculated as follows: $\sum_{K_1=0}^{T} (T - K_1 + 1) = \frac{(T+1)(T+2)}{2}$ By constraining our optimization problem with (23), the number of possible parity packet allocations for K_3 will be $\lfloor \frac{T}{3} \rfloor$ and for each case of K_3 there are $(\lfloor \frac{T - K_3}{2} \rfloor + 1 - K_3)$ possible parity packet allocations for both K_1 and K_2. Thus, the number of possible parity packet allocations will be calculated as follows: $\sum_{K_3=0}^{\lfloor \frac{T}{3} \rfloor} (\lfloor \frac{T - K_3}{2} \rfloor + 1 - K_3)$ which, in the worst case, is equal to $\frac{(T+1)(T+5)}{12}$. Therefore the ratio of possible allocations in this last case to the full search case is $\frac{(T+5)}{6(T+2)}$. For large T, this ratio will be equal to $1/6$ which shows reducing the number of possible parity packet allocations up to 83%. In this optimization problem, we assume that $M_{GOP}(i)$, the total transmission budget of GOP i is known. To find this budget, we use an offline approach similar to the one utilized by the LDO technique.

More specifically, we find the rate-distortion curve of the decoder first. Then, we calculate the probability of recovering each frame under the given channel condition and the given parity for each column of that frame. Using (18), the distortion of GOPs are calculated. This process is repeated for all possibilities of the parity allocation limited by the total amount of parity for each GOP. Having identified all allocations and associated distortions, the optimal parity allocation in the GOP and minimum distortion of GOP are calculated for a given channel condition.

C. Multi Layer FGS

In this section, we focus on the transmission of the EL bitstream. Based on the characteristics of the utilized codec, decoding of the EL of each frame depends only on the BL of the same frame. Thus assuming the BL of a frame is received correctly, we can appropriately split the budget available to the EL bitstream between data and parity portions of the EL. In the rest of this section, we first evaluate the proposed analytical distortion model for the case of an FGS bitstream.

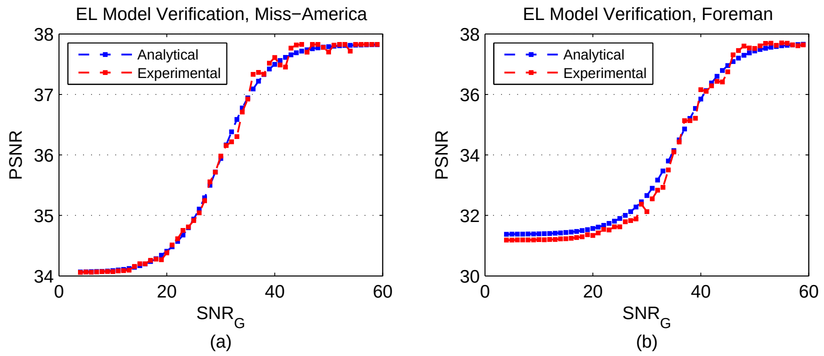

Fig. 5. A comparison of analytical and experimental distortion results for (a) FGS layer of Miss-America sequence and (b) FGS and FGST layers of Foreman sequence.

Next, we propose a one-dimensional optimized RS code to protect the EL bitstream against both bit errors and packet erasures using our distortion model.

1) Modified Expected Distortion Model: Based on the above assumption, the probability of receiving the BL bitstream of each frame is equal to one. Using (10), we can calculate the distortion of each frame including both BL and EL bitstreams, individually as follows:

$$d_{Frame} = \sum_{i=1}^{E+1} D_{Frame}(i-1)\mathcal{P}_{es}(1-\mathcal{P}_{es})^{(i-1)} \tag{24}$$

In Equation (24) E is the length of the EL bitstream for the current frame, $D_{Frame}(i)$ is the distortion of the current decoded frame when the BL and first i bytes of the EL bitstream are received error free, and $\mathcal{P}_{es}$ is the probability of symbol error. As mentioned before, $\mathcal{P}_{es}$ is calculated using Equation (1).

We evaluate the accuracy of our modified analytical expression by comparing it with the output of our utilized codec. We experiment with several video sequences. Fig. 5 illustrates sample results of our experiment for Miss-America and Foreman sequences. The results show the accuracy of our analytical model. While not shown, we note that the results of our experiments have been consistent for a variety of sequences and symbol sizes.

2) Distortion-Optimal Transmission: Now, we formulate another constrained optimization problem associated with the transmission of the EL over a channel characterized by tandem loss. The optimization problem is targeted at minimizing the expected distortion of the EL bitstream and is subject to a total transmission budget for the EL bitstream of a frame. We protect the packetized EL bitstream with a fixed packet size against the loss effects of the tandem channel. We note that the availability of FGS feature allows the decoder to reconstruct the video bitstream from prefixes of EL bitstreams. This means that the allocation of video bitstream data and FEC parity can be dynamically adjusted according to channel conditions. The latter constitutes yet another rate allocation problem. In the discussion below, N is the number of packets, L is the length of each packet formed in the horizontal direction, L_s is the number of channel coding symbols in each packet, and N_s is the number of packets containing the EL data of a frame. We introduce four methods for solving the rate allocation problem of this section. As illustrated by Fig. 6(a), one method is to use a product code in which the data block is protected equally against both bit errors and packet erasures. Receiver checks each received packet for bit errors and corrects errors if possible or else it marks the packet as corrupted. When all N packets are received, the symbols of each column are corrected and decoded. As our source data is progressive, the ratio of data and parity for each block of data can be optimized by performing a search on the possible range of parity numbers. We call this method Search on Equal Error Protection (SEEP). Another method is described in [23] in which source symbols are protected unequally against bit errors while packets are protected equally against erasures. This scheme searches for the optimal values of N_s and L_s. Therefore, we call this method 2-dimensional search method and refer to it as S2D1. Fig. 6(b) illustrates the operation of this method. The details of optimization process for the transmission of a progressive bitstream associated with an image utilizing this method can be found in [24]. We extend this method for transmitting a video sequence formed by a number of frames relying on the expected distortion model of in (24). We note that per frame complexity of this method is $O(N^2L)$. It is also possible to protect the bitstream against bit errors equally while using unequal protection against the packet erasures. Fig. 6(c) describes this method to which we refer as S2D2. In [11], the details of optimization using this method of transmission for a progressive image are provided. The optimization of this method has a per frame complexity of $O(NL^2)$. Once more, we extend this method for transmitting a video sequence formed by a number of frames using (24). In the last two methods, UEP is used in one direction and EEP is used in the other direction of the bitstream block. Fig. 6(d) shows the proposed method to which we refer as O1D. In this method a one-dimensional coding scheme in the vertical direction is applied to a sequence of horizontally formed packets. Considering temporally correlated nature of loss, it is also important to note that applying RS coding across vertical columns results in interleaving of the symbols thereby improving performance. In what follows, we describe the details of our O1D method. Using (24), we measure the expected distortion of EL of one frame transmitted as:

$$d_{Frame} = \sum_{i=1}^{L+1} D_{Frame}(i-1)\psi_{C_i}\prod_{j=1}^{i-1}(1-\psi_{C_i}), \tag{25}$$

where C_i is the number of parity symbols for the i-th column, L is the length of packets, $D_{Frame}(i)$ is the distortion of the decoded frame when the first i columns of data are received or reconstructed, ψ_{C_i} is the probability of failing

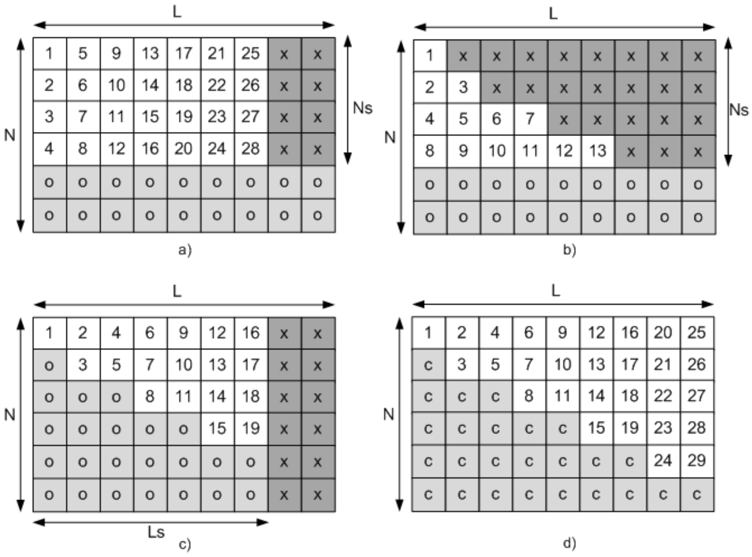

Fig. 6. Transmission systems of (a) SEEP, (b) S2D1, (c) S2D2, and (d) O1D.

to reconstruct the i-th codeword or column, and $\psi_{C_{L+1}} = 1$. Based on correction power of RS code with C parity symbols ψ_{C_i} can be defined as:

$$\psi_{C_i} = 1 - \sum_{j=0}^{C_i} \mathcal{P}(N_{err} \leq \lfloor \frac{C_i - j}{2} \rfloor | N_{ers} = j) \mathcal{P}_{ers}(N, j), \quad (26)$$

$$\mathcal{P}(N_{err} \leq \lfloor \frac{C_i - j}{2} \rfloor | N_{ers} = j) = \sum_{k=0}^{\lfloor \frac{C_i - j}{2} \rfloor} \mathcal{P}(N_{err} = k | N_{ers} = j), \quad (27)$$

$$\mathcal{P}(N_{err} = k) | N_{ers} = j) = \begin{pmatrix} N-j \\ k \end{pmatrix} \mathcal{P}_{es}^k (1 - \mathcal{P}_{es})^{N-j-k}, \quad (28)$$

where $\mathcal{P}_{es}$ is the probability of symbol error and $0 \leq C_i < N$. It is important to note that ψ_{C_i} considers the effects of both symbol errors and symbol erasures. The optimization problem for each frame is defined as:

$$\min_{\mathbf{C_1}, \mathbf{C_2}, \ldots, \mathbf{C_L}} d_{Frame} \quad (29)$$
$$\text{subject to} : 0 \leq C_i < N, \; i \in \{1, 2, ..., L\}$$

where $\psi_{C_{L+1}} = 1$, $D_{Frame}(0) = \sigma^2$, and σ^2 is the variance of the source.

This optimization problem can be solved with an $O(NL)$ complexity using the local search algorithm [25] or the distortion-optimal solution proposed in [26] and [24]. We have used the latter algorithm which solves L single variable optimization problems instead of solving an optimization problem with L decision variables. It is shown in [26] that although the i-th optimization problem consists of i columns, only the first column has to be optimized.

V. Comparison Results

In this section, we provide our numerical comparison results. In Section IV-A, we proposed a method for allocating the total budget between the BL and EL bitstream of an encoded video sequence. Referring to Table II, we utilize the total budget to protect the BL without transmitting the EL under poor channel conditions. In Subsection V-A, we provide the comparison results of our proposed OSL technique with other alternative methods under poor channel conditions. In Subsection V-B, we present the performance of our technique for other channel conditions. In all cases, the BL is allocated enough parity budget such that it is received free of errors. While the EL is also transmitted, the budget allocated to it and consequently its performance vary depending on channel conditions.

In our experiments, the GE chain is used to capture temporally correlated pattern of bit errors. For the GE chain, we apply transitioning probabilities of $\gamma = 0.99875$ and $\beta = 0.875$ associated with average burst lengths of 800 and 8 bits. We choose an SNR range of $[4, 60]$dB for GOOD state of the GE chain and set $SNR_{\mathcal{G}}$=10 $SNR_{\mathcal{B}}$ to differentiate between the two states. An independent G chain is used to capture temporally correlated pattern of packet erasures. The G chain has the same γ as the GE chain and its β parameter changes in the range of $[0.87625, 0.995]$. In this work, we also use robust header compression [27] to compress the RTP/UDP/IP header into 3 bytes. This will help reduce the overhead of packetizing the video bitstream.

While we have experimented with a variety of sequences, we only report our results for Miss-America sequence encoded in two layers and Foreman sequence encoded into three layers due to the space limitation.

A. Poor Channel Condition

Now, we provide the comparison results of our proposed technique OSL with those of ELP and LDO techniques for different channel conditions and total budgets. To provide same transmission conditions for all methods, we assume that the intra-coded frames are protected with enough amount of parities to achieve the threshold of our model, in the same way as the OSL method.

The comparison results of OSL, LDO, and ELP techniques for Miss-America sequence are shown in Fig. 7(a) and 7(b). While in Fig. 7(a) the total transmission budget is fixed, in Fig. 7(b) the results are shown for different budgets and a fixed channel packet loss probability. As shown in Fig. 7(a), the ELP method cannot recover packet losses and therefore its quality is fixed at the basic level under all channel conditions. This is only the case when I frames are received with a

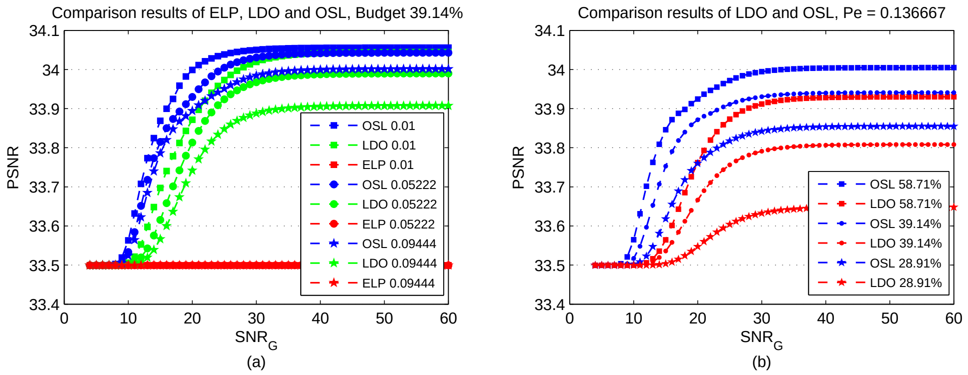

Fig. 7. The comparison results of (a) OSL, LDO, and ELP techniques for Miss-America sequence under different channel conditions when a parity budget equal to 39.14% of the size of the original video bitstream is utilized, (b) OSL and LDO techniques for different budgets and different bit error conditions.

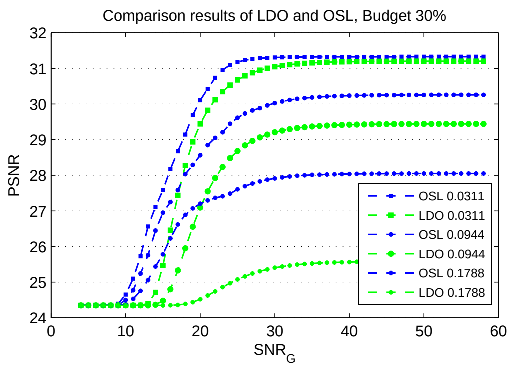

Fig. 8. The comparison results of OSL and LDO techniques for Foreman sequence under different channel conditions when a parity budget equal to 30% of the size of the original video bitstream is utilized.

probability greater than the threshold value of the model. As shown in Fig. 8, the comparison results of OSL and LDO methods for the Foreman sequence with three layers are similar to the results of the two-layer encoded bitstream.

B. Other Channel Conditions

Here, we provide the results of comparing S2D1, S2D2, SEEP, and O1D methods for the transmission of the EL using different budgets. The total budget and packet size are assumed to be fix for all of the transmission methods. We notice that the size of the EL bitstream for all frames of test video sequences such as, Foreman, Miss-America, and Grandma are almost equal. Therefore, we assume that our total budget for the whole sequence is divided equally between all frames. We note that for the cases in which EL bitstreams of the frames are unequal in size, their importance in the quality of the sequence is different and as such the budget is assigned based on their importance. The result for a choice of total transmission budget applied to the EL bitstream of Miss-America and Foreman sequences in qcif format are presented in Fig. 9. In Fig. 9, the total budget for transmitting the EL bitstream of Miss-America is 140% of the size of the EL bitstream and the packet size is 20 bytes. For the Foreman sequence, the total budget for transmitting EL bitstream is 108% of the total size of the EL bitstream and the packet size is 16 bytes. As shown in the figure, our proposed O1D method outperforms the other two product codes, S2D1 and S2D2, and all three methods outperform SEEP especially for small values of SNR_G.

VI. Conclusion

In this paper we proposed a model for analytically capturing the expected distortion of a multi layer video bitstream. We attempted at transmitting multiple bitstreams over a tandem channel introducing fading related bit errors and network buffering related packet erasures. Utilizing our distortion model and MoMuSys video codec implementing MPEG4 standard with FGS, we formulated and solved two distortion-optimal problems of video transmission over a tandem channel. In the first problem, we introduced an optimal technique for transmitting a single layer bitstream. In the second problem and under the assumption of having already delivered the bitstream based on the proposed solution to the first problem, we proposed a distortion-optimal scheme for transmitting an enhancement layer bitstream. We compared the performance of both proposed distortion-optimal solutions with other UEP methods as well as an optimal EEP method. Our results illustrated that our proposed solutions outperform other methods for both low and high quality channel conditions.

References

[1] M. Schaar and H. Radha, "Unequal Packet Loss Resilience for Fine-Granular-Scalability Video," *IEEE Trans. on Multimedia*, Dec 2001.

[2] T. Fang and L. P. Chau, "A Novel Unequal Error Protection Approach for Error Resilient Video Transmission," *in Proc. IEEE Int. Symp. Circuits System*, May 2005.

[3] C. Haung and S. Liang, "Unequal Error Protection for MPEG-2 Video Transmission over Wireless Channels," *Signal Processing Image Communications*, Jan 2004.

[4] X. Y. et al., "Unequal Loss Protection for Robust Transmission of Motion Compensated Video over the Internet," *Signal Processing Image Communications*, Mar 2003.

[5] T. Fang and L. P. Chau, "GOP-based channel rate allocation using genetic algorithm for scalable video streaming over error-prone networks," *IEEE Trans. on Image Processing*, Jun 2006.

[6] P. A. Chou and Z. Miao, "Rate-distortion optimized streaming of packetized media," *IEEE Trans. on Multimedia*, Apr 2006.

[7] P. Cuetos and K. W. Ross, "Unified framework for optimal video streaming," *In Proc. INFOCOM*, 2004.

[8] F. Zhai, Y. Eisenberg, T. N. Pappas, R. Berry, and A. K. Katsaggelos, "Rate-distortion optimization product code forward error correction for video transmission over IP-based wireless networks," *In Proc. ICASSP*, 2004.

[9] S. Zhao, Z. Xiong, and X. Wang, "Optimal resource allocation for wireless video over CDMA networks," *In Proc. ICME*, 2003.

[10] V. Stankovic, R. Hamzaoui, and Z. Xiong, "Joint product code optimization for scalable multimedia transmission over wireless channels," *In Proc. ICME*, 2002.

[11] ——, "Real-time error protection of embedded codes for packet erasure and fading channels," *IEEE Trans. on Circuits Syst. Video Technol.*, Aug 2004.

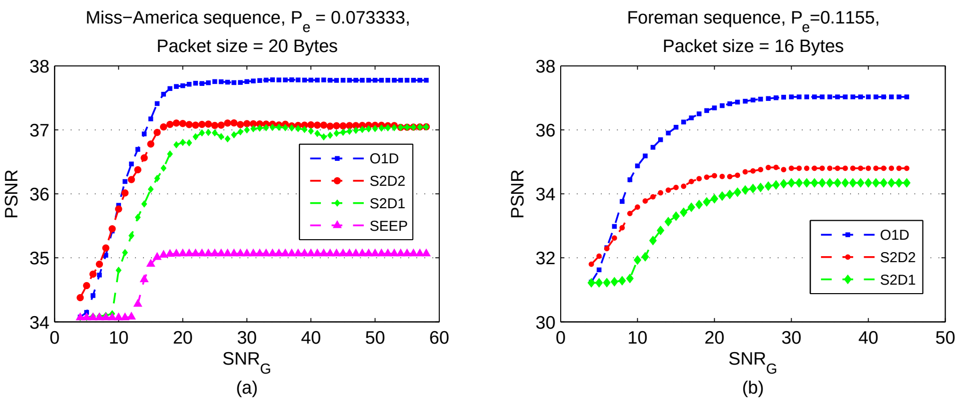

Fig. 9. Comparison results of (a) Miss-America sequence for a total budget equaling 140% and (b) Foreman sequence for a total budget equaling 108% of the size of the original bitstream.

[12] "General project information, the momusys web site," *available at http://www.tnt.uni-honnover.de/project/eu/momusys/*.
[13] "Final report on standardisation activities, MoMuSys Public Deliverable," *available at http://www.tnt.uni-honnover.de/project/eu/momusys/doc/mom-docs.html*.
[14] G. H. Park, W. H. YOO, and D. Y. SUH, "H.264-based selective fine granular scalable video coding," *IEICE Trans. on Communication*, Aug 2006.
[15] W. Li, J. Ohm, M. V. Schaar, H. Jiang, and S. Li, "MPEG–4 video verification model," *ISO/IEC/JTC1/SC29/WG11/N3908*, Jan 2001.
[16] W. Li, "Overview of fine granularity scalability in MPEG–4 video standard," *IEEE Trans. on Circuits Syst. Video Technol.*, March 2001.
[17] "MPEG–4 fine granular scalability verification model version 4.0," *ISO/IEC/JTC1/SC29/WG11/N3317*, 2000.
[18] H. Yousefi'zadeh, F. Etemadi, and H. Jafarkhani, "Distortion-optimal transmission of progressive images over channels with random bit errors and packet erasures," *In Proc. DCC*, 2004.
[19] H. Yousefi'zadeh, H. Jafarkhani, and M. Moshfeghi, "Power optimization of wireless media systems with space-time block codes," *IEEE Trans. Image Processing*, Jul 2004.
[20] J. Nonnenmacher, E. Biersack, and D. Towsley, "Paritybased loss recovery for reliable multicast transmission," Sept. 1997.
[21] D. Rubenstein, J. Kurose, and D. Towsley, "Real-time reliable multicast using proactive forward error correction," *In Proc. NOSSDAV*, 1998.
[22] V. K. B. Stephen B. Wicker, "Reed-solomon codes and their applications," 1999.
[23] F. Etemadi, H. Yousefi'zadeh, and H. Jafarkhani, "Progressive bitstream transmission over tandem channels," *In Proc. ICIP*, 2005.
[24] F. Etemadi and H. Jafarkhani, "An efficient progressive bitstream transmission system for hybrid channels with memory," *IEEE Trans. on Multimedia*, 2006.
[25] R. Hamzaoui, V. Stankovic, and Z. Xiong, "Rate-based versus distortion-based optimal joint source channel coding," *In Proc. DCC*, 2002.
[26] F. Etemadi, H. Yousefi'zadeh, and H. Jafarkhani, "A linear-complexity distortion optimal scheme for transmission of progressive packetized bitstreams," *IEEE Sig. Proc. Letters*, May 2005.
[27] S. Casner and V. Jacobson, "Compressing IP/UDP/RTP headers for low-speed serial links," *RFC2508*, Feb. 1999.

Negar Nejati received her B.S. degree in computer engineering from Esfahan University of Technology, Esfahan, Iran in 1996 and her M.S. degree from Sharif University of Technology in 2002. She is currently a Ph.D candidate in the department of Electrical Engineering and Computer Science (EECS) at University of California, Irvine. Her research interest is in the area of video transmission over wireless channels with a focus on optimal resource allocation for improving the QoS of multimedia transmission applications. She has held two summer internships at Broadcom Inc. and Digital Spectrum Solutions Inc. In 2007, she received the Center for Pervasive Communications and Computing (CPCC) fellowship.

Homayoun Yousefi'zadeh (SM'06) received the B.S. degree from Sharif University of Technology, Tehran, Iran, the M.S. degree from Amirkabir University of Technology, Iran, and the Ph.D. degree from University of Southern California (USC), Los Angeles, all in Electrical Engineering, in 1989, 1993, and 1997, respectively. He is currently an Associate Adjunct Professor of the Department of EECS at the University of California, Irvine. He also holds a Consulting Scientist position at the Boeing company. Most recently, he was the CTO of TierFleet, Inc., a Senior Technical and Business Manager at Procom Technology, and a Technical Consultant at NEC Electronics. Dr. Yousefi'zadeh has served as the chairperson of the systems' management workgroup of the Storage Networking Industry Association, and a member of the scientific advisory board of the Integrated Media Services Center at the USC. He is an associate editor of the IEEE Communications Letters and an editor of the IEEE Wireless Communications. In the past, he has served as the lead guest editor of IEEE JSTSP the issue of April 2008 and the TPC member of various IEEE conferences.

Hamid Jafarkhani received the B.S. degree in electronics from Tehran University in 1989 and the M.S. and Ph.D. degrees both in electrical engineering from the University of Maryland at College Park in 1994 and 1997, respectively. He is currently a Chancellor's Professor at the Department of EECS, University of California, Irvine. Dr. Jafarkhani ranked first in the nationwide entrance examination of Iranian universities in 1984. He was a co-recipient of the American Division Award of the 1995 Texas Instruments DSP Solutions Challenge. He received the Best Paper Award of ISWC in 2002, the 2006 IEEE Marconi Best Paper Award in Wireless Communications, and an NSF Career Award. He also received the UCI Distinguished Mid-Career Faculty Award for Research in 2006 and the School of Engineering Fariborz Maseeh Best Faculty Research Award in 2007. He is an area editor for the IEEE Transactions on Wireless Communications. He is listed as a highly cited researcher in http://www.isihighlycited.com. According to the Thomson Scientific, he is one of the top 10 most-cited researchers in the field of "computer science" during 1997-2007. He is an IEEE Fellow and the author of the book "Space-Time Coding: Theory and Practice."