Dynamic Adaptive Forward Error Control Framework for Image Transmission Over Lossy Networks

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ABSTRACT

In this work, we address the problem of transmitting JPEG compressed image over a lossy network. We introduce a combination of block level Triangular Interleaving Scheme (TRII), and Variable and Selective Forward Error Correction scheme (VS-FEC) to make the transmitted data more resilient while using the network bandwidth more efficiently in the presence of bursty losses. Our results show that TRII barely affects the final compression ratio of the transmitted image (on the average just 4% below JPEG), while considerably increases its resilience to errors. Also, in the presence of losses, a new scheme is introduced to dynamically add a variable FEC to avoid retransmission of the lost data. Small amount of FEC overhead was needed (4%, versus 10%-15% in constant FEC) to be at least 90% sure on the average that the protected information will not be damaged during transmission.

Keywords: Forward Error Control, Error Concealment, Image Transmission, Interleaving, JPEG.

1. Introduction

Image and video information loss and its recovery is still one of the biggest concerns in today's high-speed digital communication networks. In spite of channel bandwidth reservation and low Bit Error Rates (BER) in ATM networks, errors are introduced in the form of cell loss due to buffer overflow during multiplexing [1]. Several approaches have been proposed in order to recover or at least ameliorate the effect of cell loss during data transmission. Among the most important are Forward Error Control (FEC) and Error Concealment (EC) with interleaving (see [2], [3], [4], [5], [12]). FEC is an open loop scheme that involves the transmission of fixed redundant information along with the original data so that in case of cell losses, this lost information can be fully recovered at the receiver. The advantage is that there is no retransmission of information as in close-loop techniques (Automatic Repeat Request-ARQ). However, adding redundancy increases the amount of information to be transmitted and so does the network load, making the cell loss rate worse [6]. If the cell loss rate (CLR) exceeds the FEC protection limits, lost cells can no longer be recovered and degradation of the information is unavoidable.

When such problems arise, EC techniques can be applied in order to decrease the effect of errors, without increasing the transmission bandwidth or modifying the standard codes. Such technique, approximate the missing information by exploiting the fact that neighboring blocks are highly correlated. Under this assumption, EC techniques attempt to fill in the corrupted area (lost block) by using information from adjacent error free blocks (still images) or previous frames in the case of video. In general, EC is useful to hide the loss of small portion of still images (or intra-frames), but are inadequate to cope with the loss of large regions or correlated bursty losses [7].

In this paper we present a technique that balances the previous two approaches (FEC and EC) by data interleaving and dynamically protecting a selective group of information that is more difficult to reconstruct via EC at the receiver's place. Our approach is *Variable* in the sense that the amount of FEC dynamically varies according to the current network error rate, that is the higher the cell loss rate, the higher the number of added FEC cells. If no errors are encountered during transmission, no FEC is added. Furthermore, our scheme is *Selective*, because not all the transmitted cells receive protection. The algorithm decides which cells should be protected to guarantee probabilistically speaking a minimal loss in image quality at the receiver.

The rest of the paper is organized as follows. Section 2 describes the proposed solution, explaining in detail the

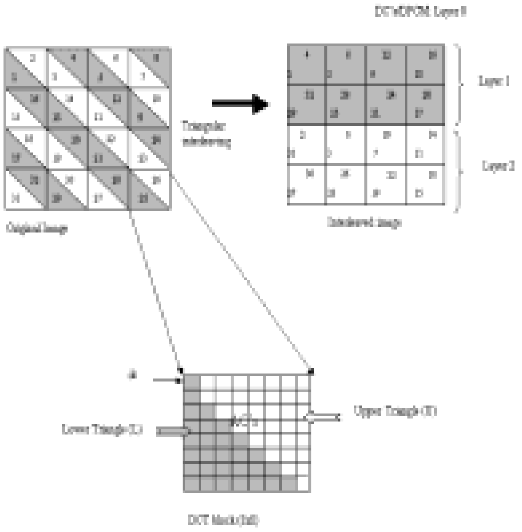

Figure 1: Triangular Interleaving (TRII) scheme.

decorrelation process and the variable-selective FEC (VS-FEC) technique. In Section 3 we describe the cell discard model and FEC cell compensation strategy. In Section 4, we present the results of the simulations and section 5 presents conclusions.

2. Proposed Solution

The proposed interleaving and VS-FEC scheme takes into account that in general cell losses are correlated and occur in burst [8]. FEC is less efficient when losses are unevenly dispersed [13]. In the same way, if the information in the cell is spatially correlated, and this cell is lost, the EC techniques will do a poor job. Because of this problem, cell information should be organized in such a way that highly correlated blocks (neighboring blocks) should not be sharing the same cell nor in *l* consecutive number of cells (because of bursty loss). The information among successive cells should be as much decorrelated as possible (see [10]). We have addressed this problem by using a Triangular Interleaving Scheme (TRII) [9], in order to de-correlate information inside the blocks and between packets after the image information has been DCT transformed and quantized. For the sake of completeness, this scheme is briefly explained below.

2.1 Triangular Interleaving (TRII)

In this interleaving scheme, two neighboring blocks exchange partial information (half of the DCT coefficients) between them, and are put as far as possible from each other during the packetization process. Therefore, if one of them is lost during transmission half of the information belonging to each block can still be retrieved at the receiver from the error free block. In this way we are increasing the probability to have at least a partially damaged block at the receiver. The Triangular interleaving scheme consists of the following steps:

a. An 8x8 block (after DCT-transformed and quantized) is diagonally divided in order to obtain two triangular components, the upper (U) and the lower (L) components (as shown in Figure 1). The main diagonal is added to the U component, except for the DC term, which is treated as an independent value.
b. After block diagonalization, a new set of blocks are created by bringing together the L triangle of the first block with the U triangle of the second block, the L of the third block with the U of the fourth block, and so on until we reach the end of the image following the row prime order scanning of the image blocks. This represents the first layer (L_1). The second layer (L_2) starts by merging the U of the first block of the image with the L of the second block, then continuing in the same way as for the first layer. DC terms are differentially encoded (DPCM) to form L_0.
c. After interleaving the blocks, variable length code is then applied (Huffman code) followed by the packetization process.

It is important to point out that every U and L belonging to the same block b_i are approximately separated by $T_c/2$ cells, where T_c is the total number of cells to be transmitted. For a block to be empty at the receiver's, the cell containing U and the one containing L both need to be lost.

The effect of TRII scheme on the compression ratio was tested on three different images Lenna, Boats, and Bridge. TRII yields on the average a compression ratio of 97% of the JPEG compression, which basically means that we are getting decorrelated information at a low cost and more resilience to cell loss errors (Table 1).

Image	Average Compression Ratio (%)
Lenna	94
Boats	97
Bridge	98

Table 1: Average percentage of compression ratio for triangular interleaving (TRII) scheme compared to JPEG.

2.2 FEC Protection

We simulate the effect of FEC described by [11], based on Reed-Solomon (RS) Burst erasure correcting code. Generally speaking, N cells that need protection are grouped together with R redundant cells which form the FEC block of size F = N + R. In this scheme at most R

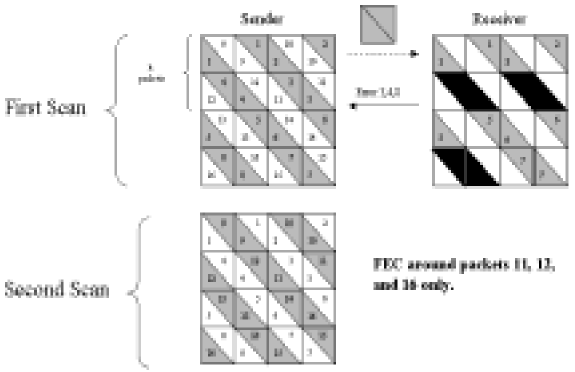

Figure 2: FEC protection scheme.

packet losses can be recovered at the receiver; any loss greater than that implies no possible recovery. In the scheme we propose, we do not apply FEC at the beginning of the transmission. The layer L_1 is transmitted without FEC and feedback is awaited from the receiver about the lost cells. While the sender is waiting for the feedback, it is sending at the same time the DC layer containing DC coefficients as a high priority layer. If there was no loss in the first layer, the second triangular layer L_2 is transmitted without FEC protection; otherwise FEC is then applied to protect information in L_2. However, a distinctive feature in our scheme is that FEC overhead is variable and selective because only information of the blocks which did not receive any data from previous layers are protected. Let's consider that during the transmission of L_1 we lost some packets corresponding to the area shown in black in Figure 2. For simplicity consider that each cell is made of the lower and upper triangular information between two consecutive blocks. Those blocks in the cells whose counterparts were not received (in this case 11, 12, and 17) are the only cells that are going to be protected by appending FEC to the second layer. By using this kind of selective protection, we increase the probability that some coefficients in every DCT block will reach the other end. The amount of FEC overhead added for protection depends basically on the network cell loss rate during the transmission of L_1, and it is computed using the stationary probabilities of a 4-states Markov model, as described in section 3.2.

3. Discard Model and VS-FEC

This section describes the cell discard model used for the simulation of a lossy network, as well as the error recovery process of the missing data. The description is adjusted for ATM networks where the DC layer can be protected by assigning it a high priority value.

3.1 Cell Discard Process

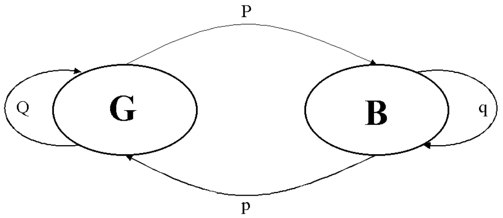

Figure 3: 2-State Markov Model.

We have evaluated the proposed VS-FEC under bursty cell loss environment, which considers consecutive cell loss process due to buffer overflow. This cell discard process can be approximated by considering a 2-state Markov model with transition probabilities as shown in Figure 3. The states *G* and *B* represent the *Good* (no cell loss) and *Bad* (cell loss) conditions respectively. The quantity *P* represents the transition probability to go from *G* to *B*, and *p* from *B* to *G*. The quantity *Q* represents the probability to stay in good state (*G*), while q represents the probability to stay in bad state (*B*). Large values of *q* represent strong tendency of consecutive discard (bursty environment), while small values ($q < 0.1$) represent random cell losses [1].

3.2 Cell Loss Compensation Strategy

As mentioned in section 2.2, we use VS-FEC to protect the transmitted information so that at least the DC layer and one of the triangular layers can reach the receiver end. After the sender has sent L_1, it continues sending the information corresponding to the DC layer and at the same time waiting for feedback from the receiver (specifying which packets were lost in the first layer), so the sender never stops transmitting information. If cell losses occurre in L_1, the FEC cells are added to L_2 to protect those packets that are carrying the complementary information of the damage blocks. The number of FEC cells to be added to L_2 for protection is approximated by considering the probability of loosing cells from both layers (1 and 2) at the same position (complementary information), as shown in Figure 4. In

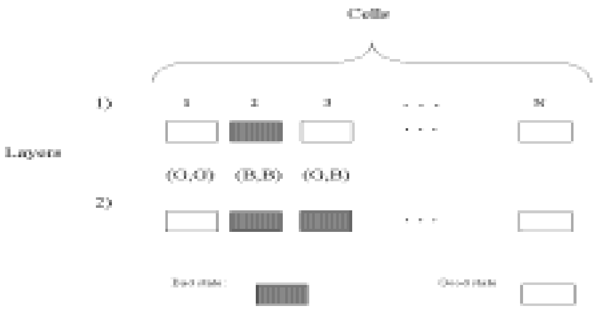

Figure 4: Joint markov model between layer 1 and 2.

this figure, the values in the parenthesis represent the state of the first and second layers, respectively. For instance, state *(B,B)* means that we lose complementary packets (this is the state that we want to avoid), and *(G,B)* means that there is no loss in L_1, only in L_2 . Assuming that the cell loss pattern in L_1 does not influence the loss pattern in L_2 (independence property), the probability to go from *(B,B)* to *(G,B)* is *pq*. By using this reasoning, the whole problem can be re-stated as a 4-states Markov Chain ($S = [(G,G),\ (G,B),\ (B,G),\ (B,B)]$) with transition probability represented as:

$$P_{i,j} = \begin{pmatrix} Q^2 & QP & PQ & P^2 \\ Qp & Qq & Pp & Pq \\ pQ & pP & qQ & qP \\ p^2 & pq & qp & q^2 \end{pmatrix} \tag{1}$$

where $P_{i,j}$ is the probability to go to state *j* given that we are in state *i*, and $i, j \in S$. The parameters *Q*, *P*, *p*, and *q* are calculated based on the information received from the sender. From this point, the stationary probabilities can be calculated by solving the following system of equations:

$$\begin{gathered} \pi_j = \sum_{i \in S} \pi_i P_{ij} \\ \sum_i \pi_i = 1 \end{gathered} \tag{2}$$

where π_j represents the long term probability to be in state $j \in S$. As we mentioned above, we are particularly interested in the value of $\pi_{(B,B)}$, which represents the fraction of cells in L_2 that will be in state *(B,B)*. From this value, we can compute the number of cells needing protection by the following relation:

$$F_c = \pi_{(B,B)} N_2 \tag{3}$$

where N_2 is the number of cells in L_2. Since we have to send F_c additional cells in L_2, and considering that the total number of losses in the FEC cells can be represented as $(\pi_{(B,B)} + \pi_{(G,B)})F_c$, then the total number of cells needing protection can be represented as:

$$F_c \geq \pi_{(B,B)} N_2 / (1 - \pi_{(B,B)} - \pi_{(G,B)}) \tag{4}$$

4. Performance of VS-FEC

This section describes the simulation results. The effectiveness of 4-MM is determined by comparing it with fixed, linear, and random FEC approaches. In the case of fixed FEC, the number of cells added for protection is determined prior to the transmission. In the case of linear FEC, the number of FEC cells is equal to the number of cells needing protection, and for the random case, the number of FEC cells is determined by using the expected value of a binomial random variable.

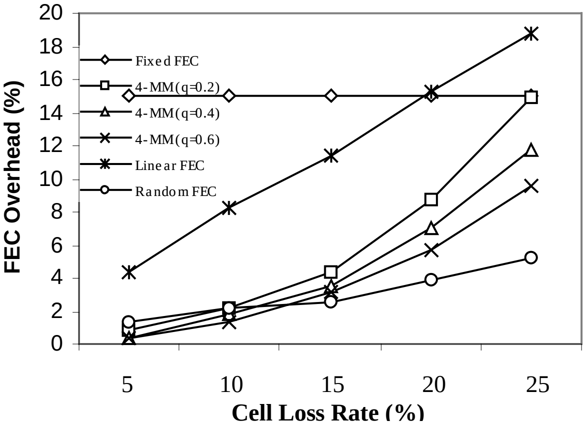

Figure 5: Percentage of overhead for protection in function of the cell loss rate.

We evaluate all of the above FEC schemes using the following three criteria: 1) Minimum amount of FEC required for cell protection; 2) Probability of survival, that is, the probability that the protected group of cells indeed reaches at the receiver; and 3) the effect of cell loss on the PSNR. For each scheme, 80 simulations were run under different cell loss rates (5%, 10%, 15%, 20%, and 25%) for different values of burstiness $q = \{0.2, 0.4, 0.6\}$, representing light bursty, bursty, and heavy bursty cell loss processes, respectively. We assume that the DC layer remains unmodified by using high priority transmission, and only the first and second layers are subject to errors. Furthermore, we keep the same error rate for both layers (L_1 and L_2 + FEC) by increasing the transmission delay of layer 2 proportional to the number of FEC cells added. We have used Lena (512x512) image at compression ratio of ~15 in our experiment.

The amount of FEC overhead for all schemes (fixed, linear, random, and 4-MM) added to L_2 (after a loss in L_1) is presented in Figure 5. Both for fixed and linear FEC schemes the amount of FEC is much greater than 4-MM for all values of *q* and for all cell loss rates. On the average the fixed FEC is 10 times and linear FEC 4.3 times greater than 4-MM for $q = 0.4$. On the other hand, random FEC is smaller for cell losses greater than 15%, and bigger for smaller losses. Comparing the FEC overhead among the 4-MM's group, it is surprising (at first sight) that smaller values of burstiness ($q = 0.2$) have greater FEC overhead under the same CLR. One of the reasons for these is that complementary blocks are not fully synchronized due to the difference in frequency content per triangular block. For instance, consider that cell 1 in layer 1 is made of the encoded blocks 1 to 20 (one block is 8x8 pixels), and cell 1 in layer 2 is made of the first 15 blocks. If cell 1 in layer 1 was lost (first 20 blocks), then we need to protect the first two cells in layer

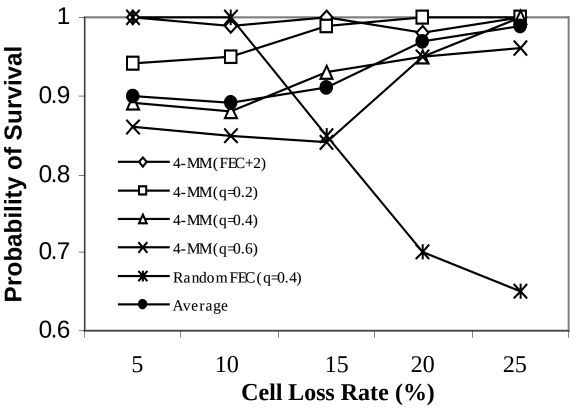

Figure 6: Probability of Survival (probability that protected cells will reach the receiver error free).

2 to make up the difference for blocks 16-20 in layer 1. In the worst case, where *K* packets are lost randomly in the first layer (very small values of *q*), we may end up protecting *2K* cells instead of K (the greater the burstiness the closer the length of protected cells and cells lost in L_1). The higher the number of cells needing protection, the higher the number of FEC cells needed in L_2. An optimization rate constraining algorithm can be applied to fully synchronize cells in both layers.

Figure 6, shows the probability that a group of protected cells will reach the receiver for random and 4-MM models under different CLR. Not shown in the figure, fixed FEC is 100% effective up to 15% cell loss rate and goes to zero afterwards, while linear FEC survives for all CLR at the expense of larger amount of overhead. Random FEC is effective for CLR less than 15% and decays considerably for higher loss rates. In the case of 4-MM, overall, the probability of survival increases as the cell loss rate becomes worse, as shown by the average curve. This is because $\pi_{(B,B)}$ and $\pi_{(G,B)}$ become more important with higher CLR, increasing therefore the number of FEC cells. For low CLR values (5%, 10%, and 15%), probability of survival basically represents the natural behavior of the system since FEC overhead is very small, less than 4%. On the average, the lowest probability of survival is around 90% for 5% CLR and increases to 99% for 25% CLR. This is indeed a robust survival probability keeping in mind that we are using the minimum FEC overhead. In general, random FEC can be used to compute FEC overhead in low CLR, while 4-MM can be used for high CLR.

In Figure 6, analyzing each 4-MM curve individually, *q=0.2* gives the best probability of survival, and *q=0.6*, the worse for all CLR. The reason is that as the burstiness increases, the probability of loosing complementary information ($\pi_{(B,B)}$) also increases. The probability of survival between 93% and 100% is achieved for *q=0.2*, 88% to 100% for *q=0.4*, and 84% to 99% for *q=0.6*. It is worth mentioning that in our 4-MM scheme, if we added 2 more cells to the FEC overhead, we were able to achieve 100% probability of survival. The additional number of FEC cells can be justified by considering that the number of FEC cells added for protection represent the expected number of cells lost at a particular error rate. This deviation can be approximated by transforming the 4-MM into a 2-MM, solving for the stationary probabilities and using the standard deviation expression of a binomial distribution.

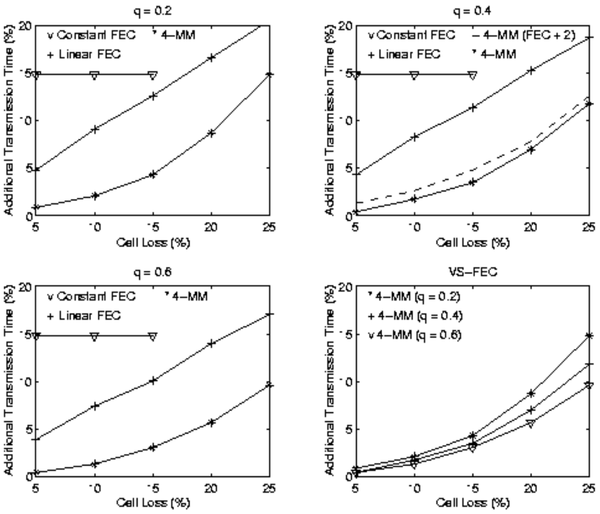

Figure 7: Percentage of time required to transmit the FEC cells with respect to the original transmission time (no FEC).

Figure 7 shows the additional time in percentage needed to transmit the protected image using fixed, linear and 4-MM, considering a 1.5Mbs transmission line. In general, the higher the number of FEC cells the better the probability of survival, but worse the transmission delay. For instance, linear FEC scheme has the problem that it over-protect the transmitted information, producing longer delays but is 100% of effectiveness. The random scheme, on the other hand produces small amounts of overhead, small delays, but provides small probabilities of survival. The 4-MM scheme generates relatively small amounts of overhead and still providing effective data protection (specially on high CLR) and low delays (2.4 times shorter than the linear case). In general, 4-MM gives an excellent trade off between overhead and survival for all values of *q*.

The PSNR for *q=0.4* is presented in Figure 8. There is no big difference in the PSNR and the visual quality as the cell loss ratio increases. This behavior points out the efficiency of TRII to disperse errors along larger regions of the image. It also points out the robustness of 4-MM in avoiding loss of the information in a given area, and guaranteeing the DC terms and one of the triangular regions for each block at the receiver's location.

5. Conclusions

We have introduced a combination of interleaving scheme in the frequency domain (TRII) and a novel variable and selective forward error control scheme (VS-FEC), to increase the resilience of the transmitted data (JPEG compressed images) to bursty losses. It is shown that the interleaving process provides additional resilience to the transmitted data with minimal compression penalties, while VS-FEC (4-MM) gives in general the best probability of survival (greater than 90%) for all CLRs and all types of network traffic loads.

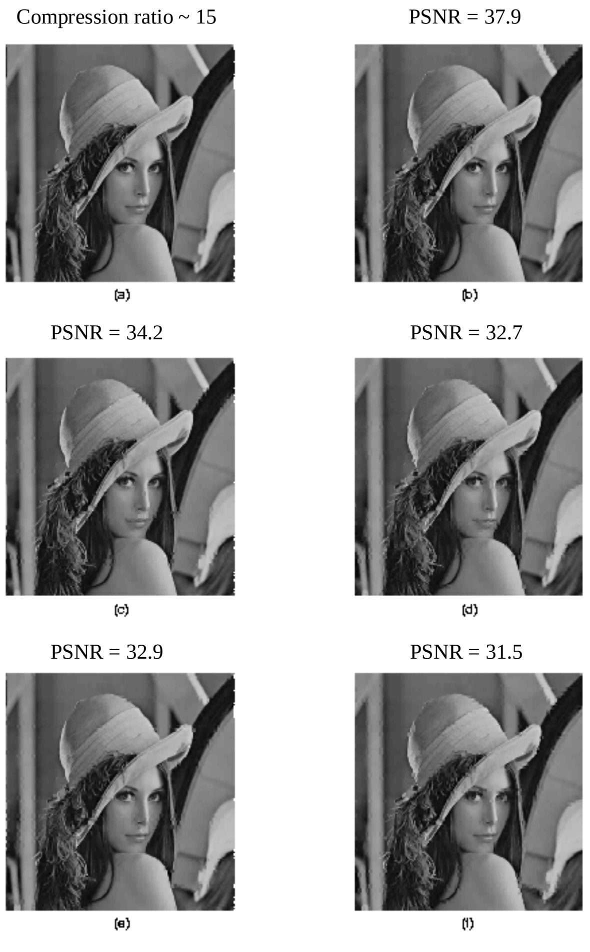

Figure 8: PSNR for different cell loss rates, under 4-MM protection. (a) Represents the original transmitted image, (b)-(f) represent the PSNR under 5%, 10%, 15%, 20%, 25% cell loss rate.

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