A FAST ERROR PROTECTION SCHEME FOR TRANSMISSION OF EMBEDDED CODED IMAGES OVER UNRELIABLE CHANNELS AND FIXED PACKET SIZE

Nikola Sprljan, Marta Mrak, Ebroul Izquierdo

Multimedia and Vision Lab, Dept. of Electronic Engineering
Queen Mary, University of London
Mile End Road, E1 4NS, London, UK
{nikola.sprljan, marta.mrak, ebroul.izquierdo}@elec.qmul.ac.uk

ABSTRACT

Joint source-channel coding enables efficient transmission of embedded bitstreams over unreliable channels. We address channels with fixed packetisation and decoding without or with minimal delays. The computation of an optimal protection scheme for such bitstreams is generally an exponential complexity problem and hence not applicable in a straightforward implementation. Using the rate-distortion characteristics of the source bitstream and the dynamic programming approach we construct an efficient unequal error protection scheme for the predefined channels. Our algorithm is of linear complexity and thus applicable in real time scenarios.

1. INTRODUCTION

Progressive image/video coders produce a bitstream such that reconstruction quality improves at the receiver as more bits are received. Applications for this functionality are broad, since it allows an instant display of a lower quality representation of an image even for very congested and narrow-band connections. Embedded encoders belong to the class of progressive encoders in which embeddedness refers to the property of the compressed bitstream that decoding of any its prefix produces lower bit-rate source representation. While these encoders show a good rate-distortion performance they are quite vulnerable to bit errors in noisy communication channels, such as wireless channels. Since the informational importance of the progressive bit-stream decreases towards the end of the stream, the occurrence of an error can have drastically different effects depending on the location of the affected bit. Furthermore, since the wireless link often only connects an end node to the rest of a heterogeneous network, loss can be also caused by congestion at routers within the network. In applications that require low transmission delay the communication is unidirectional and without retransmission requests. Therefore, congestion usually leads to a discarding of the packets, so the occurrence of loss of entire packets has to be considered in the design of robust communication systems.

A significant amount of work has been conducted recently on efficient transmission of progressively coded images over different kinds of unreliable channels and networks, [1]-[5]. However, most of the proposed solutions assume a variable channel packet size, where a packet represents one Rate-Compatible Punctured Convolutional (RCPC) codeword, i.e. the trellis of the Viterbi decoder begins with the first bit and terminates with the last bit of the packet. This concept is suitable for channels where data is transmitted as a consecutive stream of bits, and where packets are used merely as a logical structure, as is the case with point-to-point wireless links. However, if at some point in the communication chain the packets are discarded due to congestion, an approach that employs a basic unit of protection that matches the packet size is needed. In addition, some applications require low latency decoding, thereby restricting the usage of solutions based on product codes, [6].

In this paper lossy channels and fixed packet size transmission are considered. In this context, we propose a solution for fast computation of an unequal error protection scheme for embedded data. Our technique creates an efficient protection scheme that gives an error-protected bitstream that can be decoded without any delays.

2. PROBLEM FORMULATION

For the protection of the embedded source bitstream, we use a concatenated RCPC/CRC scheme (as in [1]-[4]) (CRC - Cyclic Redundancy Check). It enables protection against errors (RCPC) and the detection of possible errors (CRC) after RCPC decoding. Since the RCPC decoder cannot determine whether the protected data has been correctly recovered, CRC bits are appended to the source bit block. Using at least 16 CRC bits, an undetected corrupted packet becomes a highly unlikely event and therefore it is not taken into account. RCPC coding adds redundant bits into the bitstream, and depending on the employed code rate r (the ratio of the number of source bits and the output bits), the source bit-stream will have a different resiliency to transmission errors.

As we address transmission with a fixed packet size, the actual partitioning of source data depends on the error protection scheme applied to the packets of source data and CRC bits, Figure 1. If Unequal Error Protection (UEP) is used, the partitioning of source data is generally irregular. Unequal error protection refers to a case when each of N packets can be coded with a different code rate r_m, where $m \in \{1,..,M\}$, M being the number of the different code rates used. UEP defines a protection scheme $\Psi = \left(r_{m_1}, ..., r_{m_N}\right)$, which determines the allocation of the code rates across packets. As a special case of unequal error protection, the Equal Error Protection (EEP) is defined by

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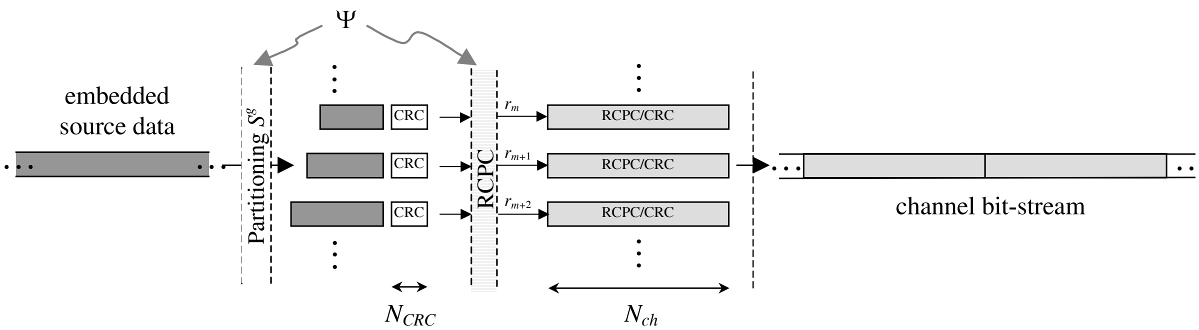

Figure 1. Schematic diagram of the system with the fixed size of channel packets for a RCPC/CRC protection

setting $r_{m_1} = ... = r_{m_N}$. The efficiency of the reception when an embedded source bitstream is transmitted depends on the used protection scheme which has to be designed taking into account both source and channel properties.

By $\rho(r_m)$ we denote the probability that the transmitted packet protected with code rate r_m will be incorrectly received. Then the probability that the first i packets during the transmission using unequal error protection have been received without an error, and that the first error has occurred on $(i + 1)$-th packet, can be written as:

$$P_i(\Psi) = \rho(r_{m_{i+1}}) \prod_{j=1}^{i} (1 - \rho(r_{m_j}))^j$$

where the probability that the first packet has been received with an error is $P_0(\Psi) = \rho(r_{m_1})$, and the probability of the correct reception of all N packets is $P_N(\Psi) = \prod_{j=1}^{N} (1 - \rho(r_{m_j}))^j$. With this notation, the expected distortion $E_N[d](\Psi)$ can be given by the sum over all possible events:

$$E_N[d](\Psi) = \sum_{i=0}^{N} P_i(\Psi) d_i(\Psi) \quad (1)$$

where d_i is the distortion when data is reconstructed with exactly the first i packets. An optimal protection scheme

$$\Psi^* = (r^*_{m_1}, ..., r^*_{m_N})$$

is then defined by

$$\Psi^* = \arg\min_{\Psi} E_N[d](\Psi).$$

If an optimal scheme is to be found from (1), the algorithm complexity would be $O(M^N)$ (exponential complexity). As this approach is impractical, the fact that the R-D function of targeted source data is decreasing can be used to constraint the number of possible solutions. That is due to $d_i < d_k$ for each $i > k$, which results in $r^*_{m_i} \le r^*_{m_k}$, i.e. $r^*_{m_1} \le \cdots \le r^*_{m_N}$, [5]. This preposition underpins the method for unequal error protection proposed in the following section. However, this constraint reduces the problem complexity to no more than $O(N^M)$ (polynomial complexity), therefore requiring some additional algorithm optimisations.

3. FAST PROTECTION SCHEME

A dynamic programming approach is proposed. Initially, the EEP problem of complexity $O(M)$ is solved, and then protection is iteratively increased from at the beginning of the bitstream and decreased from the end. In that way, protection schemes given with consecutive iterations converge to the optimal UEP.

The actual algorithm works on the disjunctive subsets of subsequent packets that have the same code ratio

$$S^g = \{n_1^g, ..., n_{H(g)}^g\}, \text{ with } r_{n_1^g} \ne r_{n_1^g - 1} \text{ if } n_1^g \ne 0.$$

The subsets cover all packets, i.e.:

$$\bigcup_g S^g = \{1, ..., N\}.$$

The protection scheme is designed with algorithm presented in Table 1. The algorithm is divided in three steps, of which a simplified example is shown in Figure 2.

The code rates are presented in decreasing order, such that $r_1 > r_2 > .... > r_N$ so that code ratios with higher indices denote higher protection. The algorithm sets the optimal EEP on all packets, and starting from that state it increases and decreases the protection in the highlighted steps (1-3 in Figure 2). After each of the iterations, the sets of subsequent packets of the same code rate that are needed for the following iteration step, are calculated. Concerning the complexity, it is now of the order $O(N)$, and the problem is solvable in real time. However, what is assumed here is that an exact operational R-D curve is known, which is generally not true for the real-time computation. This issue can be alleviated by estimation of the R-D curve in the transform domain for the selected points and by fitting it to the parametric model, [8].

In addition to the proposed UEP scheme, a simple product code scheme using systematic R-S (Reed-Solomon) coding is used. To constrain the delay introduced with R-S decoding when a packet loss occurs, we limited the number of packets in one R-S codeword. Since the R-S coding is applied across the packets, in one (N_i, k) codeword k is the number of original RCPC/CRC packets protected with $N_i - k$ redundant packets. In this joint R-S RCPC/CRC system the EEP optimisation problem is to perform a search over all (N_i, k, r_m) possible combinations. Since in our tests we experienced that the performance generally improves with N_i, for finding the optimal solution we set N_i to its maximum value defined by the maximum requested delay.

Table 1. Algorithm for UEP scheme

Step 0 – Initialisation:

- compute optimal EEP code rate

$$r_m^* = \arg\min_{r_m} E_N[d]\left(r_m\right)$$

and set the protection scheme code rates to the values of r_m:

$$\Psi = \left(r_m^*, ..., r_m^*\right);$$

- set $S^1 = \{1, ..., N\}$

Step 1 – Loop on the transition set

While the decrease of $E_N[d]\left(\Psi\right)$ is feasible*, repeat:

Step 1.A – Increase of protection

For current S^g sets check the efficiency of higher protection starting from $h = 1$ for each set:

- compute $E_N[d]\left(\Psi'\right)$ for $\Psi' = \left(r_{m_1}, ..., r'_{n_h^g}, \ldots, r_{m_N}\right)$, where r_i' denotes the code ratio that is one level higher than r_i. If

$$E_N[d]\left(\Psi'\right) < E_N[d]\left(\Psi\right), \qquad (2)$$

then set $r_{n_h^g}$ to higher code ratio. Update the protection scheme $\Psi = \Psi'$ and if $h < H(g)$ repeat this procedure for $h + 1$. If (2) is not fulfilled, the following packets from S^g at this stage do not require more protection.
- compute S^g sets of the new partitioning.

Step 2.A – Decrease of protection

For current S^g sets check the efficiency of lower protection starting from $h = H(g)$ for each set:

- compute $E_N[d]\left(\Psi'\right)$ for $\Psi' = \left(r_{m_1}, ..., r'_{n_h^g}, \ldots, r_{m_N}\right)$, where r_i' denotes code ratio that is for one level lower than r_i. If

$$E_N[d]\left(\Psi'\right) < E_N[d]\left(\Psi\right), \qquad (3)$$

then set $r_{n_h^g}$ to the lower code ratio. Update the protection scheme $\Psi = \Psi'$ and if $h > 1$ repeat this procedure for h - 1. If (3) is not fulfilled, the preceding packets from S^g at this stage do not require less protection.
- compute S^g sets of the new partitioning.

Step 3 – Completion

Ψ is declared as the optimal protection scheme Ψ^*.

*Since the behaviour of the R-D function partly depends on the used algorithm and since non-orthogonal wavelet filterbanks are used, the local maxima are also taken into account here.

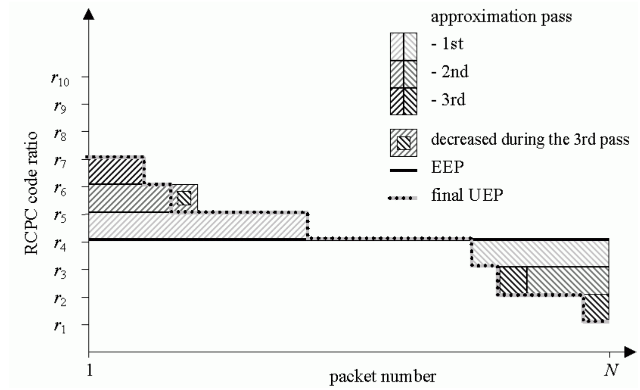

Figure 2. A diagram of the fast computation scheme for the efficient UEP protection

Table 2. Test channels

BSC	AWGN$_1$
$\varepsilon = 10^{-2}$	$E_s / N_0 = -0.86$dB ($\varepsilon = 10^{-1}$)
AWGN$_2$	**GE**
$E_s / N_0 = 4.32$dB ($\varepsilon = 10^{-2}$)	$P_{BG} = 1/400$, $P_{GB} = 1/9\ P_{BG} = 1/3600$, $\varepsilon_G = 5\cdot10^{-4}$, $\varepsilon_B = 10^{-1}$

5. EXPERIMENTAL RESULTS

The tests have been carried out for networks with fixed packet size and for four different channels (Table 2). The bit rate for each channel has been set to $R_{ch} = 128000$ bps, the packet size is $N_{ch} = 256$ bit and the transmission duration is 1 second. Available code rates are {1/3, 4/11, 2/5, 4/9, 1/2, 4/7, 2/3, 4/5, 8/9}, which were obtained with the method from [9].

The simulated channels are the following (Table 2): BSC (Binary Symmetric Channel), AWGN (Additive White Gaussian Noise) and GE (Gilbert-Elliot). The difference between BSC and AWGN channels is in RCPC decoding, namely between using the Viterbi algorithm with hard or soft decisions. It is therefore interesting to observe the difference in performance between BSC and AWGN$_2$ channels: since they have the same bit error rate ε, the difference is caused only by RCPC decoding. BPSK modulation is assumed for relating the signal-to-noise ratio E_s / N_0 of AWGN channels to its corresponding bit error rate. GE channel, although simplistic, captures well the behaviour of the channel under fading conditions where packet loss ratio varies significantly over time, as is the case with wireless links. The channel model is defined with the bit error rates of the two possible states, G and B ('good' and 'bad'), and with the transitional probabilities between them.

For the R-S RCPC/CRC system we determined the parameter N_i by requesting at least 15 decodings per second, thus setting $N_i = 33$. We then performed a dynamic search on the (k, r_m) plane, leading to the optimal (k^*, r_m^*).

Table 3. Results for the protection scheme defined by the optimal code rate r_m^*, the proposed UEP protection scheme Ψ^* and joint R-S RCPC/CRC (k^*, r_m^*)

	BSC$_1$			AWGN$_1$			AWGN$_2$			GE$_1$		
	r_m^* (= 1/2)	Ψ^*	(k^*, r_m^*)	r_m^* (= 1/3)	Ψ^*	(k^*, r_m^*)	r_m^* (= 2/3)	Ψ^*	(k^*, r_m^*)	r_m^* (= 1/3)	Ψ^*	(k^*, r_m^*)
$\overline{PSNR}$ [dB]	32.72	33.03	33.82	28.99	29.24	31.45	34.23	34.59	35.12	30.39	30.85	31.05
$\Phi^{-1}(0.9)$ [dB]	32.78	32.61	33.84	27.75	28.13	31.47	34.28	34.66	35.14	30.62	30.38	27.31
$PSNR_{max}$ [dB]	32.78	33.35	33.84	30.62	30.75	31.52	34.28	34.76	35.14	30.62	31.32	33.61
$\Phi(PSNR_{max})$	99.1%	78.9%	98.8%	79.9%	62.1%	63.7%	100%	83.6%	95.1%	92.3%	60.4%	44.7%
g [dB]	/	/	/	10.3	10.4	10.7	6.1	6.2	6.4	9.3	9.4	9.5

As an embedded source bitstream, we use the standard test image "Lena" encoded with a Set Partitioning in Hierarchical Trees (SPIHT) image coder, [6]. The test evaluates the performances of EEP, proposed fast UEP and joint R-S RCPC/CRC methods in terms of *PSNR*, its cumulative distribution $\Phi(x) = p(PSNR > x)$ and coding gain g. Coding gain refers to the required increase in E_s / N_0 for transmission of the unprotected source bitstream over the same channel, producing the same mean *PSNR*. Mean *PSNR* is computed via mean *MSE* (Mean Square Error) that is given by averaging over 1000 simulated transmissions of the test image. $PSNR_{max}$ denotes the maximum obtainable *PSNR* value while $\Phi(PSNR_{max})$ is the probability that this value is achieved. The results are summarised in Table 3.

The gain of UEP over EEP for a wide range of tested channels can be as much as 0.5 dB in mean *PSNR*. Further improvement is obtained with R-S coding where mean *PSNR* can increase over 2 dB for AWGN$_1$, Figure 3.

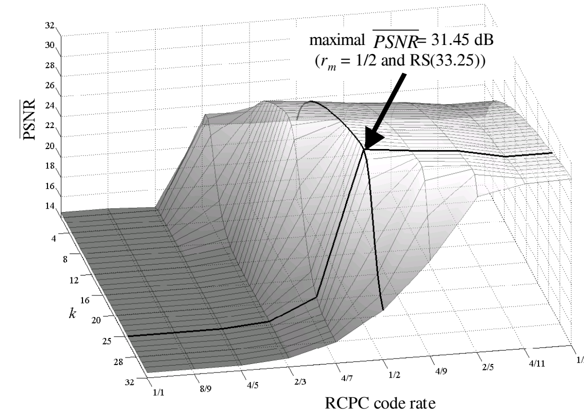

Figure 3. Mean PSNR results for all (k, r_m) for AWGN$_1$

5. CONCLUSION

The algorithms for fast computation of the efficient unequal error protection scheme and for a joint R-S RCPC/CRC coding have been proposed. They target the communication links with fixed packet size and transmission of embedded image bitstreams. While keeping the computational cost low, the UEP algorithm computes protection scheme that introduces improvements over EEP scheme. If some decoding delay is tolerated, a proposed fast algorithm for R-S RCPC/CRC coding can further significantly increase performance. Although it is presented only for one particular image coder, the approach is universal, being only constraint that the R-D function of the source is decreasing. Thus, it can be used for other embedded media content coders, e.g. JPEG-2000 and scalable video coders.

6. REFERENCES

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