ERROR RESILIENT MQ CODER AND MAP JPEG 2000 DECODING

Marco Grangetto, Enrico Magli, Gabriella Olmo

CERCOM - Center for Multimedia Radio Communications
Dipartimento di Elettronica - Politecnico di Torino
Corso Duca degli Abruzzi 24 - 10129 Torino - Italy
Ph.: +39-011-5644077 - FAX: +39-011-5644099
E-mail: `grangetto(magli,olmo)@polito.it`

ABSTRACT

In this paper a novel error resilient MQ coder for reliable JPEG 2000 image delivery is designed. The proposed coder uses a forbidden symbol in order to force a given amount of redundancy in the codestream. At the decoder side, the presence of the forbidden symbol allows for powerful error correction. Moreover the added redundancy can be easily controlled and the proposed coder is kept backward compatible with MQ. In this work excellent improvements in the case of image transmission across both BSC and AWGN channels are obtained by means of a maximum a posteriori estimation technique.

1. INTRODUCTION

JPEG 2000 [1] has definitively changed the traditional approach to still image compression by providing a variety of tools and features, that enlarge the scope of the standard beyond the mere improvement in coding efficiency. The ability to provide fine grain quality and resolution scalability, the definition of region of interest and the introduction of error resilience options are significant examples of the novel approach [2]. Moreover, Part 8 (JPIP), *Interactive protocols* and Part 11 (JPWL), *Wireless applications*, are particularly interesting from the point of view of the communication technologies, and aim at integrating the novel compression standard with the emerging market of multimedia personal communications.

In this paper we focus on the target application of wireless imaging, which is foreseen to play a major role in 3G and beyond scenarios. The error resilience tools provided by Part 1, 2 and 3 are recognized to guarantee a sufficient degree of protection when the transmission conditions are not severe, but exhibit unsatisfactory performance in presence of the harsh wireless channel. The basic resilience tools are essentially based on the insertion of markers at the codestream level, and on the termination of the arithmetic coder after each coding pass at the entropy coding level [3]; these methods provide the decoder with error detection capabilities and allow one to skip the decoding of erroneous sections of the codestream, thus preventing the propagation of the transmission errors at the image level. It is worth noticing that, since the decoder simply conceal the errors, the obtained image quality can be heavily impaired in case of severe transmissive conditions. In such a situation, the use of forward error correction (FEC) codes turns out to be vital. Several approaches based on FEC were proposed in the literature. In [4] reliable image delivery across a lossy packet network is obtained by means of an optimal Reed-Solomon codes allocation, yielding unequal error protection and graceful degradation. In [5] and [6] convolutional codes and turbo codes are applied. A concatenated scheme based on rate compatible punctured convolutional codes is presented in [7].

In this paper we propose a novel error resilience tool for JPEG 2000, based on joint source-channel coding; the coding redundancy is introduced by means of a modified MQ arithmetic coder, which allows for excellent error correction at the receiver side, thus greatly outperforming the standard concealment approach implemented in Part 1. Moreover, the proposed approach turns out to be very flexible in terms of coding rate, and scalable in terms of decoding complexity. It is worth noticing that the proposed technique has been submitted for inclusion in Part 11 of JPEG 2000; however, the reader should take the final standard, not this paper, as the definitive reference.

2. RESILIENT MQ

The JPEG 2000 entropy coding engine is a binary context adaptive, multiplication free arithmetic coder, known as MQ coder [1, 3]. It is well known that arithmetic coding is very sensitive to bit errors, due to the poor resynchronization capability of the decoder [8, 9, 10]. In [8] the introduction of a forbidden symbol in the input alphabet is employed for error detection, and allows to implement intelligent retransmission policies. The use of a forbidden symbol was investigated further in [9, 10, 11], where error correction strategies were introduced; in particular in [9, 10] maximum a posteriori (MAP) decoding was applied to a simple non adaptive arithmetic coder. Another approach to error correction of arithmetic codes was independently proposed in [12], where soft resynchronization markers are employed, instead of a supplementary forbidden symbol. The main contributions of the present work are the proposal of a resilient *MQ coder with forbidden symbol* (MQF), and the design of a MAP estimation algorithm for robust JPEG 2000 image decoding.

2.1. MQF coder

MQ encodes the decision bits $\mathbf{D} = \{d_0, \ldots, d_{L-1}\}$, corresponding to an image transformed codeblock, which are obtained by

---

This work was partially supported by the Italian Ministry of Education and Research under the CERCOM (Center for Multimedia Radio Communications) and PRIMO (Reconfigurable Platforms for Wideband Wireless Communications) grants.

0-7803-8554-3/04/$20.00 ©2004 IEEE.

means of EBCOT algorithm [3]; each decision d_i is accompanied by its own context label $x_i, i = 0, \ldots, L-1$; 9 contexts per each type of bit assure a sufficient degree of adaptivity. The encoding task is based on the recursive probability interval partition, known as Elias coding; at each iteration the interval is split in two sub-intervals, and the code string $\mathbf{C}$ is adjusted so as to point to the base of the sub-interval, that corresponds to the input symbol d_i. The probability model is adapted to the source statistic by means of a 46 states automaton that, given the current model and input symbol, updates the probability Q_e of the least probable symbol (LPS) for the next iteration. Moreover MQ partitions the interval without using multiplications; in fact, the probability interval A is guarantee to be in the range $0.75 \leq A < 1.5$, so that the following approximations are assumed (see Fig. 1-(a)):

- if the LPS occurs, the interval is reduced to $Q_e \simeq A \cdot Q_e$;
- if the most probable symbol (MPS) occurs, the interval is updated to $A - Q_e \simeq A - A \cdot Q_e$; in this case Q_e is added to the code string $\mathbf{C}$, in order to make it point to the base of the MPS sub-interval.

It is important to notice that in the practical implementation, which adopts a proper renormalization of the probability interval, the encoded bits can be output sequentially; in particular a variable number of bits $\mathbf{C}_i$ can be released in each iteration i.

The MQF coder is a simple modification of the MQ, based on the introduction of a forbidden region with probability Q_f at the base of the probability interval. The following 3 sub-intervals are identified (see Fig. 1-(b)):

- forbidden sub-interval $Q_f \simeq A \cdot Q_f$;
- LPS sub-interval $Q_e \simeq A \cdot Q_e$;
- MPS sub-interval $A - Q_e - Q_f \simeq A - A \cdot (Q_f + Q_e)$.

Obviously, at each iteration Q_f is added to $\mathbf{C}$, in order to skip the forbidden region. It is worth noticing that the encoder complexity is almost the same as standard MQ, since only one supplementary summation is needed. On the other hand the forbidden region allows for error detection at the decoder side, which is able to stop decoding as soon as the received code $\mathbf{C}$ happens to fall into the forbidden region, $\mathbf{C} < Q_f$. It can be easily demonstrated that the error detection probability approaches 1 as the number of decoded symbols increases; clearly error detection is faster when Q_f is larger. In [8] it is demonstrated that the coding redundancy, conveyed by Q_f, amounts to $-\log_2(1 - Q_f)$ bit per input symbol. Finally it is important to observe that MQF is backward compatible with MQ in the limit case $Q_f = 0$, and therefore the interoperability with JPEG 2000 Part 1 is guaranteed.

2.2. MAP decoding

In the following it is assumed that the MQF decoder observes a code string $\mathbf{R} = \{r_0, \ldots, r_{N-1}\}$, eventually corrupted by the channel noise. In presence of noise the decoder goal is to estimate the best code string $\hat{\mathbf{C}} = \{\hat{c}_0, \ldots, \hat{c}_{N-1}\}$, that does not cause a forbidden symbol detection. Consequently, the decoding task can be formulated as a constrained MAP estimation problem:

$$\begin{cases} \hat{\mathbf{C}} = \arg\max_{\mathbf{C}} P(\mathbf{C}/\mathbf{R}) \\ \text{subject to undetected forbidden symbol} \end{cases} \tag{1}$$

The a posteriori probability (APP) $P(\hat{\mathbf{C}}/\mathbf{R})$ can be expressed as follows:

$$P(\mathbf{C}/\mathbf{R}) \propto P(\mathbf{R}\,/\mathbf{C}) P(\mathbf{D}) \tag{2}$$

being $P(\mathbf{R}/\mathbf{C})$ the transition probability of the channel and $P(\mathbf{D})$ the *a priori probability* of the decision bits decoded from the codestring $\mathbf{C}$. The fist term depends on the adopted channel model, e.g. in our simulation the BSC or the AWGN channel. For the evaluation of the second term, the probabilities $P(d_i, x_i)$, adaptively estimated by the MQ decoder for each context x_i, can be used to obtain $P(\mathbf{D}) = \prod_{i=0}^{L-1} P(d_i, x_i)$.

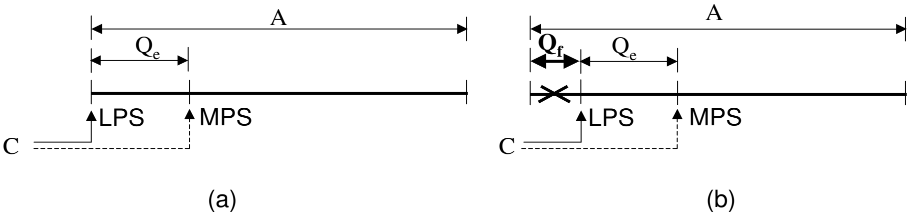
The search for the best candidate $\hat{\mathbf{C}}$ is performed by means of the decoding tree, reported in Fig. 2, which represents all the possible code sequences of length N. On the horizontal axis the bit index $j = 0, \ldots, N-1$ is reported; each node corresponds to a certain MQF decoding state σ_j, i.e. the state information for all EBCOT contexts at the j-th iteration; moreover the node stores the value of the APP, corresponding to the first j bit of the received string. Each transition between two nodes is associated with a decoding step. Let us focus on a given node at depth j in the tree, as in Fig. 2: the two departing transitions are labelled with the opposite estimates $\hat{c}_j = 0$ and $\hat{c}_j = 1$ respectively; along each branch, given the state σ_j and the estimated bit $\hat{c}_j$, a decoding step is performed, thus obtaining a variable number of decoded bits $\mathbf{D}_j$, according to the contexts $\mathbf{X}_j$ requested by EBCOT decoding passes. If a forbidden symbol is detected, the branch is pruned; otherwise the final state σ_{j+1}, along with the updated APP , is stored in the subsequent node. The *a priori* contribution to the APP, can be evaluated according to the bits $\mathbf{D}_j$, decoded in states $\mathbf{X}_j$; the channel transition term in Eqn. (2) is obtained by comparing the received and the estimated strings up to the j-th bit. Clearly, the decoder goal is to pick up the survivor path $\hat{\mathbf{C}}$ with the maximum APP. However, for usual codeblock lengths N, is unfeasible to explore the whole binary tree, which grows exponentially with the bit index j, and a suboptimal search technique is essential to solve the problem. The well known M algorithm [13] is used to this purpose; this algorithm limits the tree breadth to the best M nodes, in terms of the adopted probability metric, at each depth j. This solution is clearly sub-optimal since the correct path may be pruned because of the limited search breadth M.

The presented error correction technique has been integrated in the JPEG 2000 VM8.6 reference software; a first codeblock decoding is attempted; in case transmission errors are detected by means of the forbidden symbol or other standard resilience tools, MAP estimation is performed. The correction routine may eventually fail because of the limited memory M; in such a case standard codeblock concealment is applied, stopping the decoder before the first detected error and moving to decode the next codeblock.

3. SIMULATION RESULTS

The proposed technique has been tested in the context of 3G wireless image transmission. Experiments for several CIF and QCIF video sequences with different coding rates have been performed. In this section, for brevity, we report the results obtained with a single frame (luminance component) of the QCIF *Foreman* sequence, coded at several rates. The performance is measured in terms of the Peak Signal to Noise Ratio (PSNR), computed as linear average of the Mean Square Error (MSE) over 1000 independent simulations.

In Tab. 1 the results, in the case of transmission across the BSC and the AWGN channel with bit error probability $p = 10^{-3}$ and $p = 10^{-4}$, are shown; the coding rates are 0.25, 0.5 and 1 bpp. The standard VM8.6 performance, obtained with the error resilience options, is reported for sake of comparison ($Q_f = 0$



(a) (b)

Fig. 1. Coding intervals adopted in MQ (a) and MQF (b) coders.

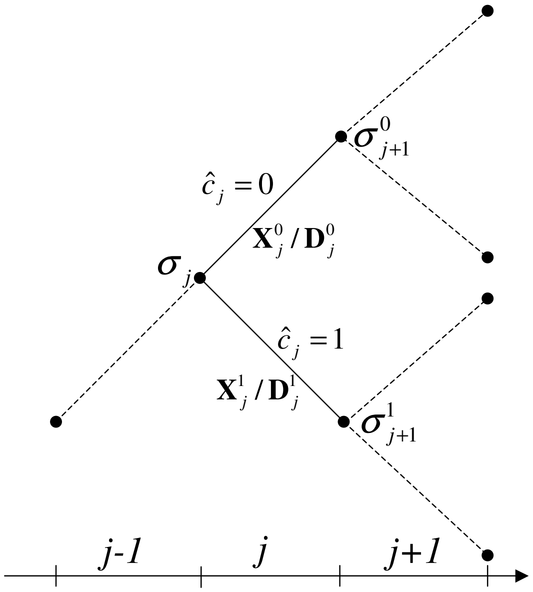


Fig. 2. Binary tree used for error correction.

in the table); in this case the enabled options are resynchronization markers, MQ terminations at each coding pass, segmentation symbol and precints. On the other hand, in the MQF case only the forbidden symbol and resynchronization markers options are used. In Tab. 1 MQF decoder, with several values of the forbidden probability Q_f, is used in three distinct configurations: i) MQF error concealment, obtained by skipping the last four coding passes upon detection of an error, and restarting with the next codeblock; ii) MQF codeblock error correction with BSC channel model; iii) MQF codeblock correction with AWGN channel model. It is worth noticing that the last experimental settings require that the soft values received from the demodulator are provided to the JPEG 2000 decoder; to this end we assume BPSK signalling over the AWGN channel. In all experiments the main and packet headers bytes are assumed to be transmitted error free, by means of a FEC code with $R_C = 0.5$; the reported values of coding rate take into account the channel coding overhead as well. The last column in the table shows the value of PSNR for error free transmission, and allows to compare the presented experiments in terms of the inserted redundancy.

First of all, it can be noticed that coding redundancy is significantly higher, i.e. peak PSNR is lower, in the VM8.6 reference case than in MQF. The gap is mainly due to the impact of the header, which is longer for the reference coder with resilience options. For example, for a coding rate of 0.5 bpp, 500 bytes of packet headers are necessary with VM8.6, and only 166 bytes with MQF; clearly, the channel coded headers heavily impact on the overall bit budget, especially in the case of small QCIF images. The comparison of the block concealment performance allows us to validate the error detection reliability of MQF; in fact, it can be observed that the proposed system exhibits similar or slightly improved concealment performance for the lowest value of $Q_f = 0.005$. However, the great advantage offered by MQF is the correction capability: the presented results for both BSC and AWGN model exhibit excellent performance. As an example, MQF decoding with BSC channel model yields a gain of more than 15 dB with respect to MQ, in the case $p = 10^{-3}$ at 1.0 bpp; in the same transmissive conditions the MQF with AWGN channel increases the gap to more than 17 dB. Obviously, given a bit error probability p, there is an optimal trade-off between the source coding rate and the redundancy offered by Q_f; in the case $p = 10^{-3}$ it can be observed that the best performance is obtained with a larger value of Q_f, with respect to the milder channel case. It is worth pointing out that the proposed MQF easily allows to adjust the coding redundancy by means of Q_f, offering a flexible means for rate adaptation. This feature represents one of the most important advantages versus conventional FEC codes, where a limited number of coding rates are obtained applying puncturing patterns. It must be pointed out that the reported excellent performance is obtained at the expense of a significant computational effort; in fact, we employ MQF with memory $M = 64$ in the case $p = 10^{-4}$ and $M = 256$ in the worst channel condition in order to reduce the number of correction failures. In the case $M = 64$ the average decoding delay for a QCIF is half of a second on a Pentium IV, 1.7 GHz, which is reasonable for a still image application.

It is well known that the average distortion is not able to capture the overall quality of the offered service. In order to better appreciate the advantage of the novel MQF decoding, in Fig. 3 the cumulative distribution function of the PSNR is shown, i.e. the probability that the PSNR is below a threshold. The reported results are carried out in the case $p = 10^{-3}$ and the performance of MQ (dash), MQF with BSC (dash-dot) and AWGN channel model is shown.

4. CONCLUSION

In this paper we have proposed a novel robust MQF coder. MQF allows to extend the error resilience capabilities of JPEG 2000, by enabling error correction strategies at entropy coding level. The new approach consistently outperforms the standard by several dBs in the case of transmission across the BSC and the AWGN channel. Finally, the decoding complexity is kept at a reasonable level by means of the proposed sequential estimation algorithm.

Table 1. Average PSNR obtained with MQ and MQF on a *Foreman* frame (QCIF).

		$p = 10^{-4}$			$p = 10^{-3}$			
Rate (bpp)	Q_f	Conceal	BSC	AWGN	Conceal	BSC	AWGN	Peak PSNR
0.25	0	22.39	-	-	17.14	-	-	25.08
	0.005	23.08	24.66	**26.63**	17.35	18.94	25.77	26.71
	0.02	23.02	**26.40**	26.50	17.27	24.43	**26.33**	26.51
	0.05	22.54	25.99	26.05	16.83	25.03	25.92	26.06
	0.08	22.23	25.64	25.65	16.59	**25.41**	25.62	25.65
0.5	0	23.91	-	-	17.46	-	-	28.84
	0.005	24.39	26.35	**30.77**	17.53	19.22	29.50	30.84
	0.02	24.32	**30.37**	30.58	17.46	26.36	**30.23**	30.61
	0.05	23.87	29.84	29.95	17.04	27.82	29.84	29.96
	0.08	23.56	29.55	29.58	16.79	**28.87**	29.54	29.58
1.0	0	24.88	-	-	17.63	-	-	33.49
	0.005	25.07	27.68	**36.48**	17.61	19.41	34.49	36.59
	0.02	24.99	**35.43**	36.12	17.55	26.59	**35.49**	36.17
	0.05	24.58	34.90	35.24	17.10	31.32	35.06	35.26
	0.08	24.29	34.37	34.39	16.86	**33.10**	34.33	34.40

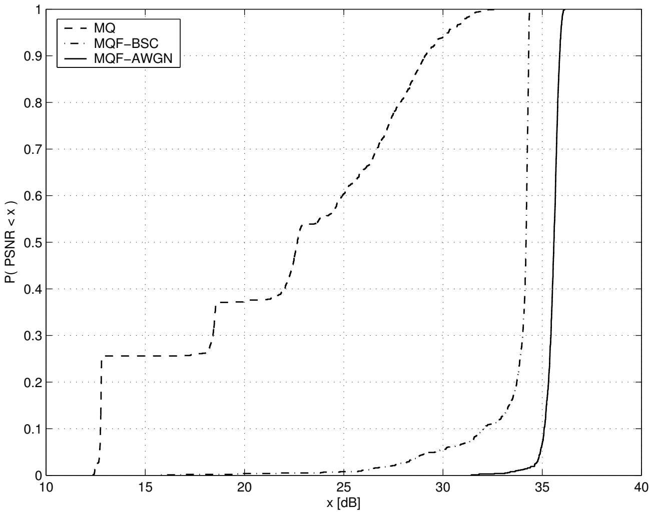


Fig. 3. Cumulative distribution of the decoded PSNR: MQ reference software(dash), proposed MQF with BSC (dash-dot), and AWGN (solid) channel model with $p = 10^{-3}$.

5. REFERENCES

[1] ISO/IEC 15444-1, “JPEG 2000 part 1 - core coding system,” 2000.

[2] C. Christopoulos, A. Skodras, and T. Ebrahimi, “The JPEG 2000 still image coding system: an overview,” *IEEE Trans. on Consumer Electronics*, vol. 46, no. 4, pp. 1103–1127, Nov. 2000.

[3] D.S. Taubman, “High performance scalable image compression with EBCOT,” *IEEE Trans. on Image Processing*, vol. 9, no. 7, pp. 1158–1170, July 2000.

[4] A.E. Mohr, R.E. Ladner, and E.A. Riskin, “Unequal loss protection: graceful degradation of image quality over packet erasure channels through forward error correction,” *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 6, pp. 819–828, June 2000.

[5] V. Chande and N. Farvardin, “Progressive transmission of images over memoryless noisy channels,” *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 6, pp. 850–860, June 2000.

[6] B.A. Banister, B. Belzer, and T.R. Fischer, “Robust image transmission using jpeg2000 and turbo-codes,” *IEEE Journal on Selected Areas in Communications*, vol. 9, no. 4, pp. 117–119, Apr. 2002.

[7] O. G. Sherwood and K. Zeger, “Progressive image coding for noisy channels,” *IEEE Signal Processing Lett.*, vol. 4, pp. 189–191, July 1997.

[8] J. Chou and K. Ramchandran, “Arithmetic coding-based continuous error detection for efficient ARQ-based image transmission,” *IEEE J. Select. Areas Commun.*, vol. 18, no. 6, pp. 861–867, June 2000.

[9] M. Grangetto, G. Olmo, and P. Cosman, “Image transmission by means of arithmetic codes with forbidden symbol,” in *Proc. of ICASSP03*, Hong Kong, Apr. 2003.

[10] M. Grangetto, G. Olmo, and E. Magli, “Robust video transmission over error-prone channels via error correcting arithmetic codes,” *IEEE Communication Letters*, vol. 7, no. 12, pp. 596–598, Dec. 2003.

[11] B.D. Pettijohn, M.W. Hoffman, and K. Sayood, “Joint source/channel coding using arithmetic codes,” *IEEE Trans. Commun.*, vol. 49, no. 9, pp. 1540–1548, Sept. 2001.

[12] T. Guionnet and C. Guillemot, “Soft decoding and sybchronization of arithemtic codes: application to image transmission over noisy channels,” *IEEE Tranactions*, to appear 2003.

[13] J. B. Anderson and S. Mohan, *Source and channel coding*, KLUWER, 1991.