BIT-PLANE ANALYSIS AND CONTEXTS COMBINING OF JPEG2000 CONTEXTS FOR ON-BOARD SATELLITE IMAGE COMPRESSION

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ABSTRACT

This paper studies the performance of the ZC contexts in JPEG2000. A quality criterion based on the mutual information is introduced. According to this criterion, there exist ZC contexts which are not effective in any bit-plane. They can thus be merged with others without significant loss of the compression efficiency. Since the contextual conditional probabilities strongly depend on the bit-planes, an adaptation of the contexts to the bit-planes is also proposed. First, an optimal context quantizer is used on each bit-planes, then a simple greedy entropy minimization procedure allows to combine the ZC contexts in JPEG2000. The results are compared with a global combination of JPEG2000 ZC contexts. Tests have been performed on a real satellite image data base. With only four ZC contexts, the PSNR is less than 0.01dB lower than the PSNR with the nine ZC contexts.

Index Terms— Image coding, Minimum entropy methods, Satellite applications, Wavelet transforms

1. INTRODUCTION

EBCOT coder [1] is one of the main parts which makes JPEG2000 among the best image compressor. EBCOT coder uses context and arithmetic coding to produce the compressed bitstream. In the domain of satellite image compression, the Consultative Committee for Space Data Systems (CCSDS) recommends the use of the wavelet transform with a bit-plane encoder [2]. But context coding is not used yet. Thus, our goal is to study the context coding in JPEG2000 and its performance with the view to adapt it for on-board compression.

Context coding is derived from universal source coding theory. The principle is to take into account previously coded samples while coding a new one. Therefore, the minimum number of bits used to code the symbol X_i of the discrete random sequence $[X_0, X_1, \dots, X_{i-1}, X_i]$ is

$$H(X_i|X^{i-1}) = -\log_2 P(X_i|X^{i-1})$$

where X^{i-1} denotes $[X_0, X_1, \dots, X_{i-1}]$. However, the conditional probability distribution $P(X_i|X^{i-1})$ is generally unknown in practice and have to be estimated. This estimation is based on an appropriate source model. In the following, as there is no ambiguity, the random variable X_i is noted X.

In context coding, this conditional probability distribution is estimated using a subset C of the sequence X^{i-1} called the modeling context. Thus, $P(X|X^{i-1})$ is estimated by $P(X|C)$. The subset C must be strongly correlated with X. Therefore, in wavelet image coding, the modeling context is formed by the neighboring coefficients. In image coding, the number of samples is often not sufficient for the convergence of the estimation $P(X|C)$. This problem is known as context dilution [3]. To avoid context dilution, the model order is reduced using a context quantizer $Q : C \to \{1, 2, \dots, M\}$ into a small number of M contexts. The conditional probability can thus be estimated by $P(X|Q(C))$. This is the context coding principle used in the JPEG2000 entropic coder EBCOT.

To reduce the coding rate, the context quantizer has to be carefully designed. This design can be done off-line to approach the minimum conditional entropy on a training image set as in MCECQ [4, 5, 6]. Liu and Karam [7] proposed an optimization scheme based on the maximization of the mutual information $I(X, Q(C))$. Recently, other optimization schemes have been proposed in which context quantization is done adaptively on-line [8, 9]. On-line optimization is not possible on-board of satellites because of the high computational capabilities it requires. Thus, this paper studies off-line context optimization by bit-planes to approach the adaptive context quantization performance. A new simple context combining method is proposed.

In section 2, a context performance measure derived from the mutual information is introduced. Using this measure, the Zero Coding (ZC) contexts of JPEG2000 are analyzed by bit-planes. In section 3, Liu and Karam optimization procedure [7] is used to produce optimal contexts by bit-planes. The results are compared to the results with the global optimization. In section 4, the ZC contexts are combined differently on each bit-planes using a greedy heuristic procedure. A comparison of the results with the global combination of JPEG2000 ZC contexts is provided. Finally, the compression performance is displayed as a function of the PSNR with a small number of contexts.

2. ANALYSIS OF JPEG2000 ZC CONTEXTS BY BIT-PLANES

EBCOT is a fractional bit-plane encoder. This means that all the bits from one bit-plane are coded in one of the three coding passes named Significant, Magnitude Refinement, and Cleanup pass. There are four primitives to encode the bits: the Run-Length (RL) primitive encodes long sequences of 0 bits, the Zero Coding (ZC) primitive encodes the bits of coefficients which have not been found significant, the Magnitude Refinement (MR) primitive encodes the bits of already significant coefficients, and the Sign Coding (SC) primitive encodes the sign bits. This paper focuses on the ZC primitive.

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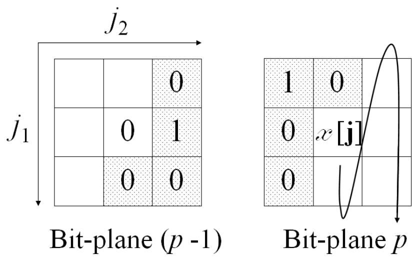

Fig. 1. Example of a modeling context C for the ZC primitive. Here the 0 and 1 denote the coefficient significance. As the scan follows the arrow, this modeling context is composed of the significance of four coefficients in the bit-plane $(p-1)$ and the significance state of the four other neighbors in the bit-plane p. In this particular case $\boldsymbol{m} = (0\ 0\ 1\ 0\ 1\ 0\ 0\ 0)$ and $m = 6$.

2.1. ZC contexts in EBCOT

The ZC primitive codes the bits at the bit-plane p from wavelet coefficients which are still not significant at the bit-plane $(p-1)$. The most significant bit-plane is numbered 1. In this primitive, the modeling context C is defined as the significance $\sigma[j_1 \pm 1, j_2 \pm 1]$ of the eight neighbors of the current bit $x[\mathbf{j}]$ with $\mathbf{j} = (j_1, j_2)$ [1]. The context quantizer Q is designed from the three intermediate quantities $\kappa^h[\mathbf{j}]$, $\kappa^v[\mathbf{j}]$ and $\kappa^d[\mathbf{j}]$ (equation 1), and the table 1.

$$\begin{aligned} \kappa^h[\mathbf{j}] &= \sigma[j_1, j_2-1] + \sigma[j_1, j_2+1] \\ \kappa^v[\mathbf{j}] &= \sigma[j_1-1, j_2] + \sigma[j_1+1, j_2] \\ \kappa^d[\mathbf{j}] &= \sum_{k_1=\pm 1} \sum_{k_2=\pm 1} \sigma[j_1+k_1, j_2+k_2] \end{aligned} \quad (1)$$

Finally, the context quantizer merges the 256 states of the random variable C into $M = 9$ contexts. In the following, the bold letter $\boldsymbol{m}$ denotes the neighbor configurations associated to the context m. The figure 1 illustrates an example in which the context is $m = 6$.

Context label m	LL, LH, and HL bands $\kappa^h[\mathbf{j}]$	$\kappa^v[\mathbf{j}]$	$\kappa^d[\mathbf{j}]$	HH bands $\kappa^d[\mathbf{j}]$	$\kappa^v[\mathbf{j}] + \kappa^d[\mathbf{j}]$
0	0	0	0	0	0
1	0	0	1	0	1
2	0	0	>1	0	>1
3	0	1	x	1	0
4	0	2	x	1	1
5	1	0	0	1	>1
6	1	0	>0	2	0
7	1	>0	x	2	>0
8	2	x	x	>2	x

Table 1. The nine ZC contexts used in JPEG2000

2.2. Context performance criterion

A context m is effective if it contributes to encode many symbols with a low conditional entropy $H_m(X|\boldsymbol{m})$. The subscript m indicates that this entropy is calculated only within the symbols for which the context is m.

$$H_m(X|\boldsymbol{m}) = -\sum_{k=\{0,1\}} P(X=k|\boldsymbol{m}) \log_2 P(X=k|\boldsymbol{m})$$

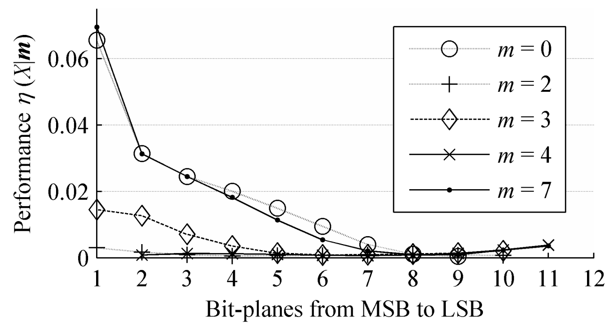

Fig. 2. Performance $\eta(X, \boldsymbol{m})$ of five ZC contexts in the LH and HL subbands of test set S1.

It can be shown that the conditional entropy $H_m(X|\boldsymbol{m})$ never exceeds $H_m(X)$ the entropy of X calculated only within the symbols for which the context is m. Therefore, the context criterion $\eta(X, \boldsymbol{m})$ is defined by:

$$\begin{aligned} \eta(X, \boldsymbol{m}) &= P(\boldsymbol{m})\,(H_m(X) - H_m(X|\boldsymbol{m})) \\ &= P(\boldsymbol{m}) I_m(X, \boldsymbol{m}) \end{aligned}$$

where $I_m(X, \boldsymbol{m})$ is similar to a mutual information between the discrete random variable X and the context $\boldsymbol{m}$. If there are few occurrences of the context m, the conditional probability $P(X|m)$ cannot be accurately estimated. In this case, $P(m)$ is low and contribute to reduce the performance $\eta(X, \boldsymbol{m})$. On the other hand, a high $P(m)$ means that conditional probability $P(X|m)$ can be accurately estimated. In this case, the performance $\eta(X, \boldsymbol{m})$ can be high if the conditional entropy in the context m is low.

The context performance have been computed on a large test set S1 of 12 bits images. This set is composed of sixteen large simulated images of size 1024×1024 from PLEIADES satellite, which will be launched in 2009, and five images of size 2048×2048 from PELICAN airborne sensor. These are earth observation images: PLEIADES images have a spatial resolution of 70cm and PELICAN images have a resolution of 20cm. These images have been compressed using the OpenJPEG [10] implementation of JPEG2000 with the 9/7 lifting wavelet filters. Three levels of decomposition have been used as in the CCSDS Recommendation [2] since it offers a good compromise between performance and complexity. After the JPEG2000 quantization, the transform images are encoded down to the last bit-plane using code-blocks of size 64×64. During the coding process, the number of bits occurring in each ZC context m has been counted. Figure 2 displays the performance of the ZC contexts (five out of the nine for clarity only).

First, it can be observed that all the context performance decreases in the less significant bit-planes. All the contexts have very low performance from the seventh bit-plane. Second, the contexts $m = 2$ and $m = 4$ present very low performance on every bit-planes compared with the high performance of the contexts $m = 0$ and $m = 7$ in the most significant bit-planes. Consequently, there is no need of context coding from the seventh bit-planes. Moreover the contexts $m = 2$ and $m = 4$ are unnecessary and may be merged with others. Thus, we propose to reduce the number of the ZC contexts in sections 3.1 and 4.1, and also to adapt the contexts by bit-planes in sections 3.2 and 4.2.

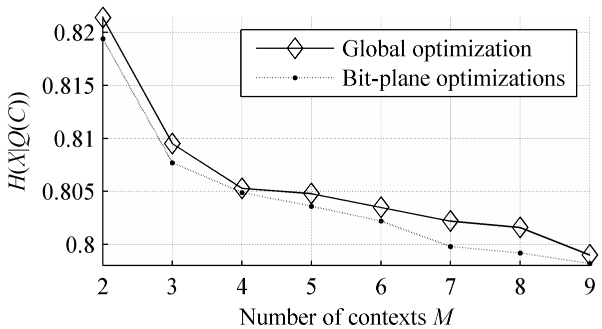

Fig. 3. Conditional entropies for different sets of optimal contexts.

3. ZC CONTEXTS OPTIMIZATION

3.1. Global Optimization

In this section, the optimization procedure described by Liu and Karam in [7] is used with the set of the 256 possible contexts C. The optimization is based on the minimization of the mutual information reduction when the states are combined into contexts. The conditional entropy can be expressed as follow:

$$\begin{aligned} H(X|Q(C)) &= H(X) - \sum_{m=1}^{M} \eta(X, \boldsymbol{m}) \\ &= H(X) - I(X, Q(C)) \end{aligned}$$

Minimizing the conditional entropy amounts to maximizing the sum of the context performance or the mutual information. Consequently, we can use their optimization procedure. This optimization is based on averaged statistics.

The optimal contexts have been computed on a training set S2 composed of fifteen PLEIADES images of size 1024×1024 and five PELICAN images of size 2048×2048. Then, these optimal contexts have been applied to the test set S1 to compute the conditional entropies with different numbers M of contexts. The results are plotted in solid line on figure 3. It can be seen that the conditional entropy decreases slowly when more than four contexts are used. Thus, in the ZC primitive, good compression results can be obtained with only four contexts.

3.2. Bit-plane optimization

Even better compression performance could be obtained by combining the contexts differently for each bit-plane. Indeed, as illustrated on figure 4, the average conditional probabilities of the nine ZC JPEG2000 contexts are similar independently of the set of images (SPOT5 5m, SPOT5 2.5m, PLEAIDES, PELICAN). Furthermore, the conditional probabilities depend on the bit-planes (figure 4).

In order to take this statistical differences into account, the same optimization procedure has been applied on each bit-plane. Instead of computing one set of optimal contexts to encode all bit-planes, a set of optimal contexts is computed for each bit-plane.

The results are plotted in dotted line on figure 3 for different numbers M of contexts. The difference in conditional entropy between the global optimization and the bit-plane optimizations is low. It is about $1.5 \cdot 10^{-3}$ on the bits coded by the ZC primitive. Knowing that the proportion of bits which is coded by the ZC primitive is 34%, this would lead to a save of about 800 bytes when a 1024×1024 image is compressed at a fix PSNR. This slight improvement is balanced by the complexity of the optimal context quantizers in the case of bit-plane optimizations.

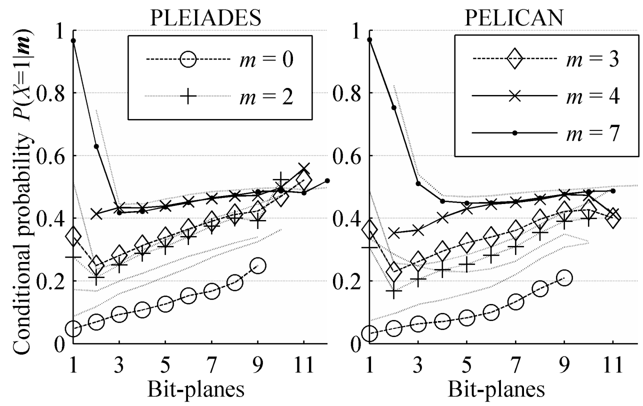

Fig. 4. Average conditional probabilities $P(X = 1|\boldsymbol{m})$ of the ZC contexts on the sets of PLEIADES and PELICAN images.

This optimization procedure, does not lead to better compression performance than with JPEG2000. Our implementation of Liu and Karam algorithm did not give the expected results [7]. Indeed, with JPEG2000, the conditional entropy on the test set S1 is 0.797 and, with four optimal ZC contexts, we obtained a PSNR about 0.07dB lower than the PSNR with JPEG2000 ZC contexts. Moreover, the design of JPEG2000 contexts is based on theoretical arguments and empirical studies [1]. Their construction is simple and regular which makes them convenient for implementation. For these reasons, section 4 considers the nine JPEG2000 ZC contexts.

4. ZC CONTEXTS COMBINING

4.1. Global contexts combining

In section 2, we saw that some of JPEG2000 ZC contexts are not relevant and that combining these contexts with others may result in a very low compression loss. Here, the goal is to combine the contexts with a limited increase of the conditional entropy.

For this purpose, we propose a greedy heuristic suboptimal procedure. This procedure successively combines the two contexts for which the conditional entropy increase is minimal, or, equivalently, for which the performance reduction is minimal. This procedure has been repeated until a given number of contexts between height and two has been reached. The combined contexts computed on the training set S2 have then been applied to the test set S1. The results are plotted in solid line on figure 5. With this procedure, the conditional entropies are lower than the conditional entropies with our implementation of the procedure of Liu at Karam.

4.2. Contexts combining by bit-planes

The same greedy procedure has been applied on each bit-plane. The results are plotted in dotted line on figure 5. The difference in conditional entropy is $2 \cdot 10^{-4}$ and would result in sparing about 100 bytes for compressing a 1024×1024 image with a fix PSNR. This poor improvement can be explained by to the predominance of the ZC primitive in only two bit-planes. Indeed, the figure 6 shows that the bit-planes mostly coded by the ZC primitive are the fourth and fifth bit-planes. In more significant bit-planes, it is the Run-Length

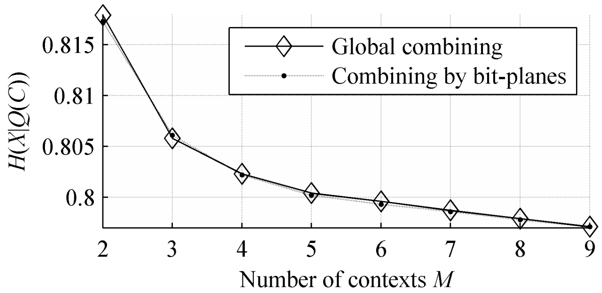

Fig. 5. Conditional entropies for different sets of merged contexts.

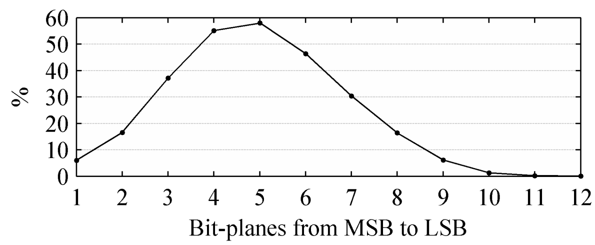

Fig. 6. Percentage of bits coded by the ZC primitive.

coding which is dominant, and in the less significant bit-planes it is the Magnitude Refinement primitive. Thus, when maximizing the performance of the ZC contexts, it is the fourth and fifth bit-planes which are the most influent. The combined contexts given by the global combining were the same as the combined contexts on these two bit-planes. This explains why the results with the global procedure are the same as the results with the procedure by bit-planes.

4.3. PSNR results

Figure 7 shows the differences between the compression with the original ZC contexts and the combined contexts in a number of $M = 3$, $M = 4$, and $M = 5$ new contexts. These new combined contexts have been obtained using the greedy procedure described in section 4.1. The curves show that the PSNR with four or five contexts are almost the same, and is less than 0.01dB lower than with the nine ZC contexts for all bit-rates. With only one context for the ZC primitive, the PSNR is about 0.3dB lower. Therefore, by using only four contexts the loss is almost negligible. The loss in mutual information may be balanced by the fact that there is slightly less context dilution with four contexts than with nine. Indeed, the four combined contexts are $m_0 = \{0\ 1\}$, $m_1 = \{2\ 5\ 6\}$, $m_2 = \{3\}$, and $m_3 = \{4\ 7\ 8\}$. The least efficient contexts have been combined with others and the new contexts are at least as efficient as the context $m = 3$. This means that all these new contexts appear frequently, thus conditional probabilities are best estimated.

5. CONCLUSIONS AND DISCUSSIONS

This paper has shown that the conditional probabilities depend on the bit-planes. However, the adaptation of the contexts to the bit-planes does not result in a meaningful increase of the compression performance. Thus, this context adaptation cannot be used for on-board satellite compression. Meanwhile, we have also shown that there are five unnecessary contexts in the ZC primitive of JPEG2000.

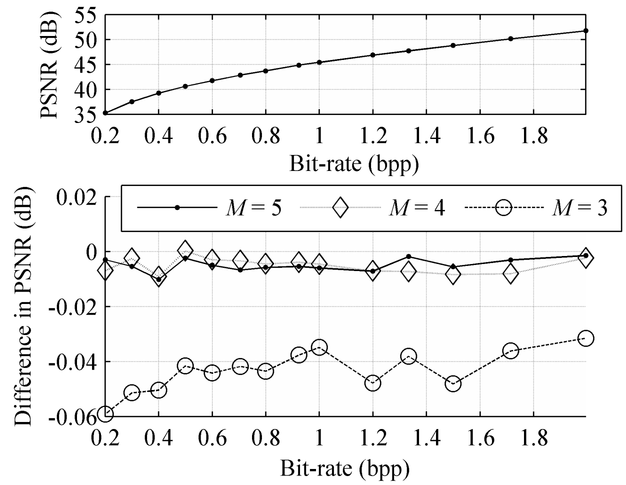

Fig. 7. Rate-distorsion curve with JPEG2000 and difference of PSNR with combined contexts.

These contexts can be simply combined with others without loss of compression efficiency.

On-board satellite, because of the scan based acquisition and the small buffer size, the image is processed by blocks of 16 lines. Thus, there is a small number of pixels available in each block. In this framework, it will be appropriate to analyze the context dilution with different numbers of contexts to select the best context quantizer.

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