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Satellite image compression by concurrent representations of wavelet blocks

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Abstract This paper proposes a complete compression and coding scheme for on-board satellite applications considering the main on-board constraints: low computational power and easy bit-rate control. The proposed coding scheme improves the performance of the current CCSDS recommendation (Consultative Committee for Space Data Systems) for a low additional complexity. We consider post-transforms in the wavelet domain, select the best representation for each block of wavelet coefficients, and encode it into an embedded bit stream. After applying a classical wavelet transform of the image, several concurrent representations of blocks of wavelet coefficients are generated. The best representations are then selected according to a rate-distortion criterion. Finally, a specific bit-plane encoder derived from the CCSDS recommendation produces an embedded bit stream ensuring the easy rate control required. In this article, both the post-transforms and the best representation selection have been adapted to the low complexity constraint and the CCSDS coder has been modified to compress post-transformed representations.

Keywords Image coding · Satellite applications · Transform coding · Wavelet transforms · Hadamard transforms

1 Introduction

Satellite Earth observation images are used in an increasing number of applications like agriculture, urbanism, mapping, or defense. This is partly due to the constantly increasing spatial and temporal resolution of on-board imagers. The counterpart is the increase of the amount of data to transmit on-ground. Image compression on-

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board satellites is thus crucial to maximize scientific data return of Earth observation missions.

When designing solutions for on-board compression, three main constraints have to be taken into account. First, the satellite orbiting around the Earth, images are acquired by a push-broom sensor scan along track. Consequently, images have a fixed width but are virtually endless. They have to be processed and compressed progressively as they are acquired. A strip-based compression is generally the solution. Second, the input bit-rate of the mass storage and the telemetry bit-rate are limited. The bit-rate at the output of the compressor should thus be limited. However, this output bit-rate depends on the image statistics and is not easily predictable. The compressor is thus expected to produce a fully embedded bit stream which can be truncated at any bit to control the output bit-rate. Third, real-time processing is required on-board. Given the amount of data, algorithms have to be implemented on space qualified integrated circuits, i.e. robust to radiations. Given the limited number of gates available on those integrated circuits, on-board algorithms must have a low complexity.

JPEG2000, the international standard algorithm for image compression, is based on the DWT (Discrete Wavelet Transform) and an entropy coder called EBCOT (Embedded Block Coding with Optimal Truncation points). However, according the CCSDS recommendation, JPEG2000 is not adapted to on-board compression. First, JPEG2000 compression is computationally intensive: three coding passes are required for each bit plane. Second, the optimal JPEG2000 rate control has high implementation complexity whereas the suboptimal rate control is inaccurate [1]. This makes the implementation of JPEG2000 on space qualified integrated circuits particularly challenging. At the time this paper is written and to the best of our knowledge, there have been very few attempts for an implementation of JPEG2000 on FPGA (Field Programmable Gate Array) [13, 15], and still none on space qualified ASIC (Application-Specific Integrated Circuits). Facing this implementation problem, the CCSDS (Consultative Committee for Space Data Systems) has issued in 2005 a new recommendation for on-board data compression: the CCSDS-IDC (Image Data Compression) algorithm [1, 14]. This algorithm is based on the DWT and on the very low complexity entropy coder BPE (Bit Plane Encoder). As it has been specially designed for the compression on-board satellite, this algorithm can process the image in the strip-based mode and produces a fully embedded bit stream. This algorithm is currently being implemented on two ASIC's by NASA Goddard and the University of Idaho [14, 6].

This paper proposes an extension of the CCSDS-IDC algorithm to increase its compression performance for a small additive complexity. The CCSDS transform and coding steps are modified. First, low-complexity concurrent post-transforms allow to reduce the residual redundancy between wavelet coefficients. Second, the BPE is modified to exploit the resulting data properties. The paper is organized as follows. Section 2 introduces the theoretical foundation of the post-transform compression scheme and modify it so that it can be employed with a progressive coder. Section 3 describes the entropy coder used, the BPE algorithm, and proposes specific modifications so that the BPE can take advantage of the entropy gain obtained thanks to the post-tranform. Finally, section 4 compares the proposed post-transform compression scheme to the original CCSDS-IDC algorithm both in terms of compression performance and in terms of computational complexity and time.

2 Post-transformed representations

2.1 The bandelets and related works

The use of concurrent representations is a recurrent idea in the image compression or approximation literature. The basic concept is to decompose the image or particular image blocks in an appropriate basis selected in a given dictionary. First the decomposition is performed in all the bases of the dictionary. Then the best basis must be found among these concurrent representations by minimizing a particular criterion. For lossy compression purpose, the criterion to be minimized involves rate and distortion after quantization. Given arbitrary sets of quantizers, the best representation selection is based on the work of Shoham and Gersho [12]. Many different dictionaries have been considered in the literature. Ramchandran and Vetterli have studied the optimal image decomposition in bases of wavelet packets [10]. Robert *et al.* have proposed to pre-process blocks of 4×4 pixels by nine concurrent circular shifts before applying the DCT [11]. The best shift provides the optimal signal orientation for DCT compression according to the rate distortion criterion. This process has been designed to enhance residual intra-frame coding in H.264. More recently, Krommweh has proposed the tetrolet transform [7]. This transform is an adaptive Haar wavelet transform on blocks of 4×4 pixels. Blocks are decomposed in many possible sets of 4 coefficients on which the Haar transform is applied. Concurrent representations come from the different possible decompositions of the blocks in sets of 4 pixels. The best representation, an orthogonal basis, minimizes a sparsity criterion.

Bandelets are also concurrent representations developped by Le Pennec and Mallat [8]. The second generation of the bandelet transform, developped by Peyré and Mallat [9], is a practical implementation by blocks of the bandelet theory. This transform aims at reducing redundancies between high magnitude wavelet coefficients resulting from the edges in the original image. Because edges are critical image features, their accurate representation should improve the uncompressed image visual quality. The blocks of wavelet coefficients are post-transformed in all orthonormal bases of the dictionary. A basis is associated to each possible direction of the edges in a block of size 4×4. In addition to these twelve directional bases, the dictionary includes the DCT (Discrete Cosine Transform) basis, two Haar bases and the canonical basis, in general the best basis for non-edges blocks. In a compression context, the basis selection is performed according to a rate-distortion lagrangian criterion (c.f. section 2.4.1).

In this paper, the proposed post-transform handles blocks of 4×4 wavelet coefficients. The concurrent representations consist in projecting the blocks into orthonormal bases. However, on-board constraints imposes an adapted dictionary composition (cf. section 2.3) and a low cost basis selection procedure (cf. section 2.4.2). Moreover, a progressive coder is adapted to encode the post-transformed representations (cf. section 3).

2.2 General principle of the post-transform

First, we propose a general post-transform process for on-board compression as illustrated by figure 1. The first step is a classical 2-D multilevel DWT. The CCSDS recommends the use of three stages of the 9/7 float DWT [1]. Next, blocks of 4×4 wavelet coefficients are post-transformed: each block f is projected on all orthonormal

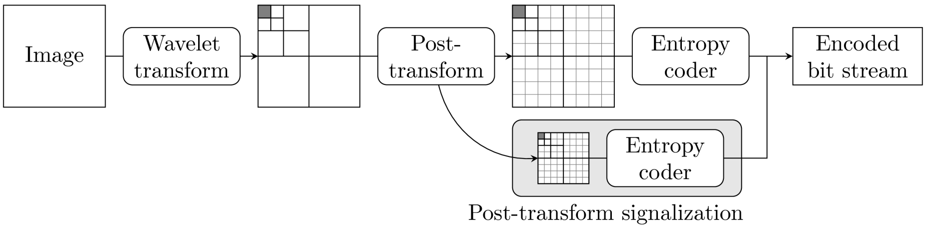

Fig. 1 Compression scheme using post-transforms

bases $\mathcal{B}_b$ of the dictionary $\mathcal{D}$. The block f can be considered as a vector of the space $\mathbb{R}^M$ with $M = 16$. The dictionary $\mathcal{D}$ is composed of $N_{\mathcal{B}}$ orthonormal bases of $\mathbb{R}^M$. The M vectors of the basis $\mathcal{B}_b$ are noted ϕ_m^b with $m \in [0, M-1]$. The vector f^b denotes the representation of the vector f in the basis $\mathcal{B}_b$:

$$f^b = \sum_{m=0}^{M-1} a_b[m]\phi_m^b.$$

The coefficients $a_b[m] =< f, \phi_m^b >$ correspond to the dot products between the vector f and vectors ϕ_m^b of the orthonormal basis $\mathcal{B}_b$. Among all the representations f^b, the best post-transformed representation f^{b*} is selected according to a bit-rate and distortion criterion detailed in the next subsection. The index b^* of the selected post-transformation is also transmitted for the post-transform inversion. This side information is called *signalization*. Finally, the signalization and the post-transformed block coefficients are entropy coded to form the compressed bit stream.

2.3 Post-transformations for on-board compression

Blocks may be post-transformed in the bandelet dictionary. Alternative dictionaries derived from statistical considerations have been devised in [4]. The post-transform bases can be derived for instance from a PCA (Principal Component Analysis) on each subband. Because on-board compression requires a low complexity, dictionaries with few bases are preferred. At the extreme, the dictionary can be composed of only one basis. There are then two concurrent representations of one block: the original and the post-transformed one (cf. section 3.3). The choice of the Hadamard basis (figure 2) is particularly attractive regarding the complexity: a projection on the Hadamard basis is simply performed by sign changes and additions. Yet, the Hadamard post-transform is efficient. In the following, the experimental results are provided for this single post-transformation.

2.4 Best representation selection

The best representation can be selected according to a rate-distortion criterion. This section first describes the Lagrangian minimization used by the original bandelet transform [9] and explains why this approach is not appropriate for on board applications. An alternative criterion is thus proposed in section 2.4.2 and compared to the Lagrangian minimization in section 2.4.3.

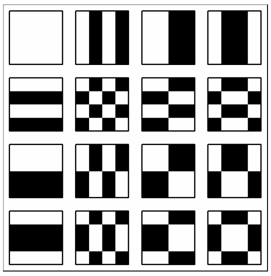

Fig. 2 The Hadamard basis for the post-transform of blocks of size 4×4

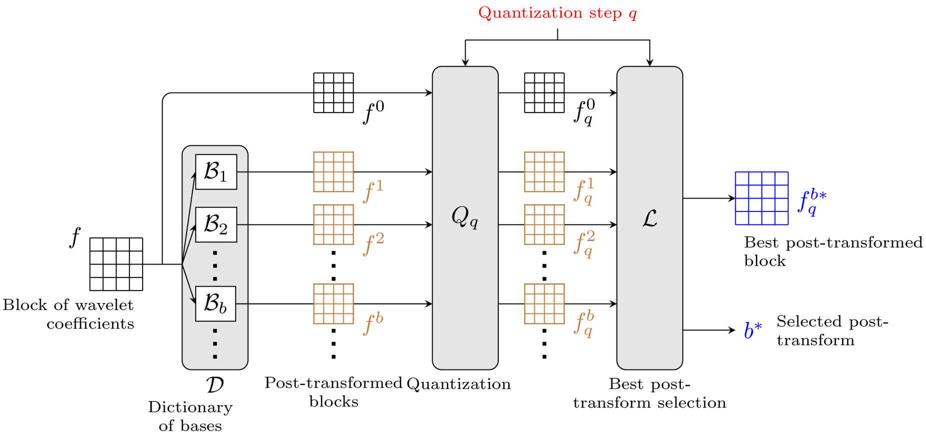

Fig. 3 Post-transform process on one block of wavelet coefficients

2.4.1 Rate-distortion minimization

The problem of the best bit budget allocation studied by Shoham and Gersho in [12] is similar to the problem of selecting the best representation of a given block in the dictionary. Lossy compression is obtained by a quantization of the post-transformed representation f^b of the block f. The resulting quantized representation is denoted f_q^b. The best representation after quantization f_q^{b*} is chosen according to a Lagrangian rate-distortion criterion:

$$f_q^{b*} = \underset{f_q^b,\, b \in [0, N_{\mathcal{B}}]}{\arg\min} \; D(f_q^b) + \lambda\, R(f_q^b), \tag{1}$$

where $D(f_q^b)$ is the least square error due to quantization of the post-transformed block f^b and $R(f_q^b)$ is an estimate of the bit-rate required for coding f_q^b and the associated signalization. Figure 3 illustrates this process. The Lagrange multiplier λ is optimized for compression [8,5].

The Lagrangian approach has two main drawbacks for on-board satellite compression. First, the estimation of the bit-rate $R(f_q^b)$ for each representation is computationally intensive and not always accurate. Indeed, at this step of the process, we do not have acces to the coefficients f_q^b we are computing. The estimation of the bit-rate $R(f_q^b)$ is thus based on the probability density of the wavelet cofficients in each subband. Second, the choice of the best representation highly depends on the quantization step q

in the rate-distortion criterion (eq. 1): the distortion $D(f_q^b)$, the rate $R(f_q^b)$ and the Lagrange multiplier ($\lambda = \alpha\, q^2$ see [5]) depends on this quantization step q. However, on-board compression requires the coder to output an embedded bit stream: the progressive encoder processes bit planes from the most significant bit (MSB) to the least significant bit (LSB). The coding process stops when the limit throughput is reached. The quantization step is therefore not defined when coding. In this context, the best representation can not be chosen using equation (eq. 1).

2.4.2 Sparcity maximization

In this paper we propose a new approach for the representation selection. It is adapted to the on-board compression constraints of low complexity and embedded bit stream. The selection is achieved by minimizing the l_1-norm of the post-transformed representation f^b. Minimizing the l_1-norm, that is, the sum of the magnitude of the coefficients (eq. 2), favors the sparsity of the selected representation [3]. The energy or l_2-norm of the block projection on each orthonormal basis remains constant, that is, equal to the energy of the original block f. On the contrary, the l_1-norm differs from one representation to the other according to their sparsity. The selected representation is the one with the fewest high magnitude coefficients:

$$f^{b*} = \underset{f^b,\, b \in [0, N_{\mathcal{B}}]}{\arg\min} \|f^b\|_1 \quad \text{with} \quad \|f^b\|_1 = \sum_{m=0}^{M-1} |a_b[m]|. \tag{2}$$

This l_1-norm minimization leads to a rate-distortion optimization adapted to on-board compression. First, the rate for coding the selected representation f^{b*} is minimized since there is a high occurrence rate of small coefficients in that representation. Second, the distortion after truncation is expected to be minimized. Indeed, the signal energy concentrates in high magnitude coefficients. In a progressive encoder, these large coefficients are mainly coded at the beginning of the embedded bit stream as they appear in the most significant bit planes. This reduces the distortion quickly. On the contrary, the numerous small coefficients are coded at the end of the embedded bit stream since they only appear in the least significant bit planes. They do not penalize the bit-rate at the beginning of the decoding process. Note that this new criterion does not depend on the quantization step q. Moreover, the costly rate estimation is not required. Finally, this new criterion is cost effective compared to the lagrangian criterion (eq. 1). This is a crucial advantage for on board compression.

2.4.3 Comparison of the selection criteria

The performance of both selection criteria have been compared for the compression of a set of satellite images. The compression scheme employed is similar to the one presented on figure 1: both the transformed coefficients and the signalization are entropy coded. According to the argumentation in section 2.3, the Hadamard basis is particularly attractive due to its very low computation complexity. We thus consider a dictionnary containing only the Hadamard basis for the comparison of the selection criteria. There are two concurrent representations: the post-transformed and the original one. According to the simulations, the l_1-norm criterion performs poorly at low bit-rates. The loss in performance comes from the signalization cost (see table 1) and

	Rate-distorsion minimization (eq. 1)		Sparsity maximization (eq. 2)	
Bit-rate (bpp)	0.5 bpp	3.0 bpp	0.5 bpp	3.0 bpp
Signalization cost (bit per block)	0.3 bpb	1.0 bpb	1.0 bpb	1.0 bpb
Signalization budget (% of the total bit-rate)	3.8%	2.1%	12.3%	2.1%

Table 1 Signalization cost associated to the different selection criteria

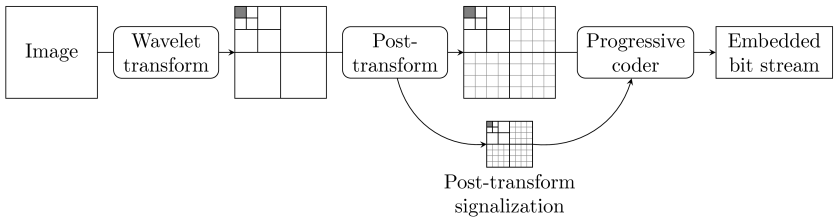

Fig. 4 Proposed progressive compression scheme using post-transforms

can be reduced by an appropriate coding in the particular case of progressive compression. For the Lagrangian criterion (eq. 1), the signalization cost is taken into account in the rate estimation $R(f_q^b)$. It is a nearly constant proportion of the global bitrate: minimizing this global rate also amounts to minimize the signalization cost. At 3 bpp, the mean signalization cost is slightly less than 1 bit per block (1 bpb) representing 2.1% of the total bit-rate. But at 0.5 bpp, this cost is 0.3 bit per block representing 3.8% of the total bit-rate. On the contrary, with the l_1-norm criterion, the representation selection does not depend on the final bit-rate. Moreover, experiments reveal that the Hadamard basis is selected as often as the canonical basis on the average. The signalization cost is thus 1 bit per block even after entropy coding and whatever the total bit-rate. This signalization cost represents 12.3% of the total bit-rate at 0.5 bpp and only 2.1% at 3 bpp. Table 1 sums up these results. The compression performance is more affected at low bit-rates than at high bit-rates. Fortunately, in the case of progressive compression, it is not necessary to transmit the whole signalization at the beginning of the bit stream. Indeed, the signalization can be progressively encoded (cf. section 3.2). Finally, sparcity optimization provides a sub-optimal solution to the rate-distortion criterion optimization. It is preferred to the more accurate Lagrangian optimization which cannot produce the embedded bit stream required for on-board applications.

3 Progressive coding

Figures 4 illustrates the simplified compression scheme devised. Both the post-transformed blocks and the signalization are progressively encoded. The BPE (Bit Plane Encoder) has been chosen has it is part of the CCSDS-IDC recommended standard [1,2]. However, modifications are required so that it can encode the post-transform signalization. In this section, the BPE is first described. Then, the modifications brought to the encoder are presented.

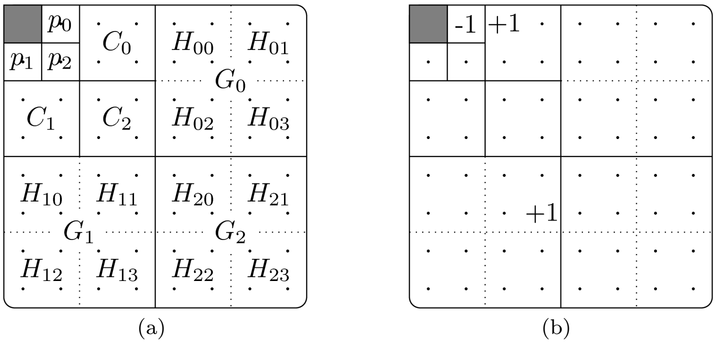

Fig. 5 (a) Sets of 64 wavelets as defined and used in the CCSDS encoder. (b) Example of bit plane, dots correspond to non significant coefficients

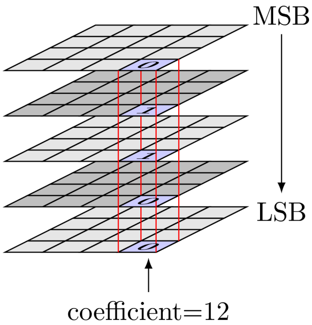

Fig. 6 Example of the representation of the coefficient value 12 in five bit planes

3.1 Introduction to the Bit Plane Encoder

The CCSDS-IDC has been specially designed for on-board satellite image compression [1]. First a wavelet transform on three levels of decomposition is performed. Then, the BPE processes blocks of 64 wavelet coefficients corresponding to 8×8 squares region of the original image. Each block contains:

- 1 coefficient of the LL_3 subband;
- 3 coefficients of the HL_3, LH_3 and HH_3 subbands, denoted p_i where $i \in [0, 2]$, defining the *parents* coefficients;
- 3 sets of 4 coefficients of the HL_2, LH_2 and HH_2 subbands, denoted C_i, defining the *children* coefficients;
- 3 sets of 16 coefficients of the HL_1, LH_1 and HH_1 subbands, denoted G_i, defining the *grandchildren* coefficients.

Figure 5(a) shows this block partition. The BPE encodes the blocks bit plane by bit plane beginning from the MSB plane to the LSB plane. In the following, a coefficient is said to become *significant* in a given bit plane when the coder encodes the first associated bit 1. For example, in figure 6, the coefficient 12 is not significant as long as the coder has not encoded the second bit plane. This coefficient is then significant in all the following bit planes. Similarly, a bit plane is said significant when at least one coefficient is significant in that bit plane. The BPE takes advantage of zero areas in the bit planes by using transition words. During the coding of a bit plane p, after coding the parents, transition words are used to signal zero areas, that is, set in which all wavelet coefficients are not significant at bit plane p. In order to localize these zero areas, the following coefficient sets are also defined:

- each set G_i is partitioned into 4 *groups* of 4 coefficients denoted H_{ij}, $j \in [0, 3]$;
- D_i denotes the list of *descendants* of a parent coefficient and is defined by $D_i = \{C_i, G_i\}$;
- B denotes the list of all descendants in a block and is defined by $B = \{D_0, D_1, D_2\}$.

The coding process of children and grandchildren is summarized in the following algorithm part of the CCSDS-IDC recommendation [1].

- Stage 2 (children)
  1. $tran_B$;
  2. $tran_D$, if $tran_B \neq 0$;
  3. $types_p[C_i]$ and $signs_p[C_i]$ for each i such that $t_{max}(D_i) \neq 0$.
- Stage 3 (grandchildren) if $tran_B \neq 0$
  1. $tran_G$;
  2. $tran_{Hi}$, for each i such that $t_{max}(G_i) \neq 0$;
  3. $types_p[H_{ij}]$ and $signs_p[H_{ij}]$ for each i such that $t_{max}(G_i) \neq 0$ and each j such that $t_{max}(H_{ij}) \neq 0$.

In the bit plane given in figure 5(b), dots correspond to non significant coefficients. The first transition word $tran_B$ is a one bit word indicating the first coefficient becoming significant in the list B. In figure 5(b), two coefficients are becoming significant in the list B, thus $tran_B = 1$. The transition word $tran_D$ indicates the lists D_i in which all coefficients are not significant (indicated by a dot on figure 5(b)). In the example $tran_D = 1, 1, 0$. In the lists D_i containing significant coefficients, the children C_i are encoded ($types_p[C_0] = 1, 0, 0, 0$ and $signs_p[C_0] = 0$, $types_p[C_1] = 0, 0, 0, 0$). The transition word $tran_G$ indicates the set G_i where some grandchildren are significant ($tran_G = 0, 1$). Finally, in the sets G_i containing significant coefficients, the transition word $tran_{Hi}$ indicates the sets H_{ij} with significant coefficients ($tran_{H1} = 0, 1, 0, 0$). The significant grandchildren of the groups H_{ij} are then encoded ($types_p[H_{11}] = 0, 0, 0, 1$ and $signs_p[H_{11}] = 0$).

3.2 Coding the post-transforms signalization

Sets G_i are composed of 4×4 blocks of grandchildren coefficients. Block candidates for post-transforms are of the same size. The post-transform is thus applied only on the first level of the wavelet transform, that is, on grandchildren blocks.

As explained in section 2.4.3, the signalization should be integrated progressively to the bit stream. Indeed, signalization is not required for blocks containing only zeros i.e. blocks which are not significant. The signalization cost is low at low bit rates since the number of such blocks is high. This cost increases with the bit rate since the number of such blocks decreases.

The signalization is thus inserted into the embedded bit stream as soon as the first bit 1 of each block is encoded. Accordingly, the encoding of the grandchildren coefficients follows the algorithm below.

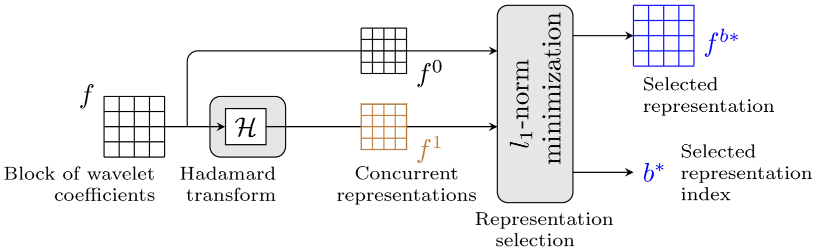

Fig. 7 Post-transform process on one block of wavelet coefficients by l_1-norm minimization

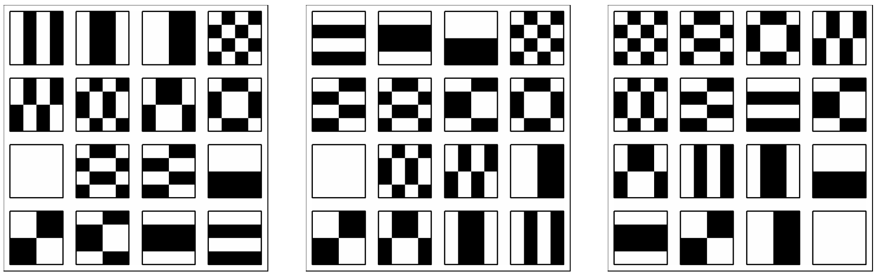

Fig. 8 Hadamard basis with in decreasing order of energy contribution for the (a) the HL_1 subband, (b) the LH_1 subband, (c) the HH_1 subband

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- Stage 3 (grandchildren) if $tran_B \neq 0$
  1. $tran_G$;
  2. s_i, for each i such that $t_{max}(G_i) \neq 0$ (signalization of the selected representation);
  3. $tran_{Hi}$, for each i such that $t_{max}(G_i) \neq 0$;
  4. $types_p[H_{ij}]$ and $signs_p[H_{ij}]$ for each i such that $t_{max}(G_i) \neq 0$ and each j such that $t_{max}(H_{ij}) \neq 0$.

The signalization word s_i indicates in which basis the block i has been post-transformed. Because there are only two concurrent representations in each subband, the signalization s_i consists in only one bit: the bit s_i indicates that the block i has been post-transformed in the ordered Hadamard basis ($s_i = 1$) or not ($s_i = 0$).

3.3 Adaptation of the post-transform to the BPE

As mentionned in section 2.3, the Hadamard basis is particularly attractive for on board application. It can thus be the only post-transform used as illustrated on figure 7.

Grandchildren coefficients are coded by groups of four coefficients H_{ij}. In order to favor zero areas in the groups H_{ij}, the basis vectors must be ordered with respect to the energy contribution. Note that the ordering is different in each subband (HL_1, LH_1 and HH_1). Figure 8 shows the ordering of the vectors for the post transform on the subband HL_1. This ordering has been defined by processing several thousands blocks of wavelet coefficients from a learning set of images. The mean value of each post-

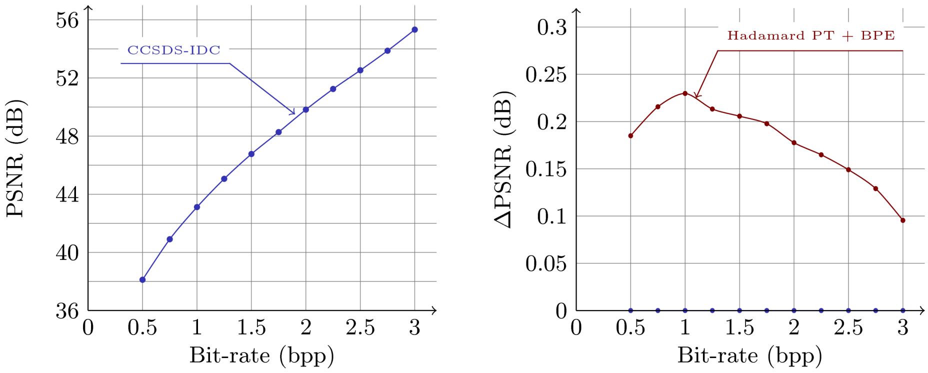

Fig. 9 (left) Results of the CCSDS-IDC algorithm. (right) Results of the Hadamard post-transform followed by the modified BPE coder relative to the results of the original CCSDS-IDC algorithm

transformed coefficient $E[a_h[m]] = E[< f, \phi^h_m >]$ has been computed. These values have been sorted by decreasing order, defining the ordering of the basis vectors. This process has been performed on each subband independently. Hence, if ϕ^h_0 denotes the upper left vector of the Hadamard basis represented on figure 8(a), the mean value of $a_h[0]$ is greater than the mean value of the other post-transformed coefficients $a_h[m]$, $m \in [1, M-1]$ in the LH_1 subband. Note the horizontal pattern in this vector adapted to the horizontal low-pass and vertical high-pass wavelet filtering. In this subband the coefficient with the lowest mean value is $a_h[M-1]$. Thus, the vector ϕ^h_{M-1} appears in the lower right corner of figure 8(a). Note that the compression could have been achieved using more than one post-transform by applying this same ordering process on the bases used. For instance, the DCT bases or Haar bases can be used.

4 Performance comparison

4.1 Compression performance comparison

Mean compression results are reported on figure 9. They have been obtained by compressing eleven very high resolution Earth observation images of size 1024×1024. Five of them are simulated PLEIADES images and have a spatial resolution of 70 cm. PLEIADES first satellite is to be launch in 2010. The other six are images from PELICAN airborne sensor with a spatial resolution of 25 cm. All images are 12-bits in depth. Hence, figure 9 shows the efficiency of the proposed compression scheme based on the post-transform of 540 672 blocks.

The gain obtained with the Hadamard post-transform and the compression scheme described in the previous sections is noted “Hadamard PT + CCSDS” on figure 9. This is the gain over the reference results obtained by compressing the same images with the original algorithm of the CCSDS-IDC recommendation (represented by the 0 dB line on figure 9). The low decay of the compression gain at high bit-rates is due to the signalization cost. It increases with the bit-rates since more and more blocks become significant. Meanwhile, the efficiency of the post-transform on low energy block is small.

Fig. 10 Simulated PLEIADES image *pleiades_portdebouc_pan* – Copyright CNES

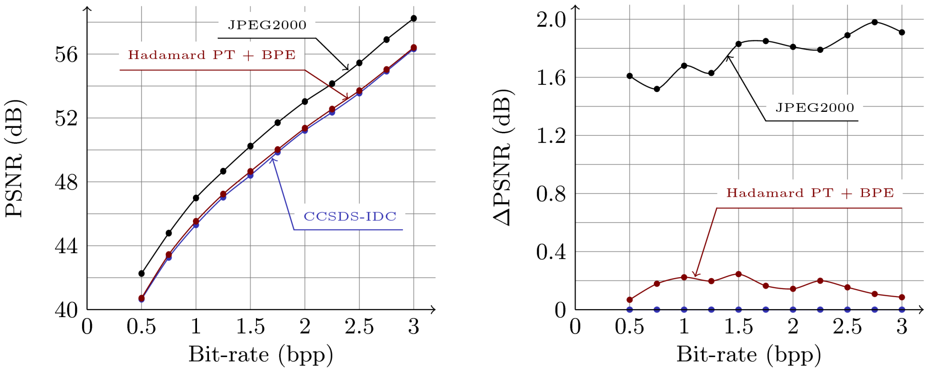

Fig. 11 (left) Compression results for the image *pleiades_portdebouc_pan*. (right) The same results relative to the results of the CCSDS-IDC algorithm

Thus, when the low bit-planes are decoded, the cost of the signalization becomes to be less compensated by the gain in PSNR.

Results reported on figure 11 have been obtained for the compression of the image *pleiades_portdebouc_pan* represented on figure 10. This is a simulated PLEIADES image of size 1400×5504 available in the CCSDS Data Compression Working Group image set[1]. Results obtained with the Hadamard post-transform are compared to those obtained with two standards: the CCSDS-IDC algorithm and JPEG2000.

Although the complexity added by the Hadamard post-transform is very low, it gives a compression gain around 0.2 dB compared to the CCSDS-IDC algorithm. Moreover, experiments have shown that the proposed post-transform compression scheme locally reduces the distortion near the edges. Indeed, since the highest wavelet coefficients are produced by edges, most of the post-transformed blocks are located at edges positions: the l_1-norm of these block is lower in the Hadamard representation. This produces high post-transform coefficients which are encoded in the begining of the embedded bit-stream and thus decoded even at low bit-rates. Usual image post-processing such as segmentation will take advantage of this property.

4.2 Computational complexity analysis and compression time

In this section, clues are given for a complexity assessment of the full compression process and the compression time is evaluated.

[1] http://cwe.ccsds.org/sls/docs/SLS-DC/BB122TestImage/ImageLib.zip

First, for each block of M coefficients, the Hadamard post-transform have to be computed. As for the Fourier transform, there exists fast algorithm to compute the Hadamard transform. This reduces the complexity of the Hadamard transform from $O(M^2)$ operations to $O(M \log M)$ additions or subtractions. Two bit shifts are also required for normalization. Then, the l_1-norm of both representations of the block are computed and compared. This requires $2 \times (M-1)$ additions and 1 comparison. If the post-transformed representation is selected, it needs to be sorted, requiring M operations. Last, encoding the signalization bit requires 1 operation per block. The complexity required is thus $M(\log_2 M + 3) + 2$ operations per block of M coefficients. Finally, only 3/4 of the coefficients are processed since only grand children coefficients can be post-transformed. The additional complexity required by the proposed algorithm is thus $3/4 \times (\log_2 M + 3 + 2/M)$ or about 5.3 operations per sample (additions, subtractions, comparisons or bit-shifts). Note that no multiplications are involved which is particularly interesting for hardware implementations where multiplications are more costly than addition and bit-shift operations. For comparison, one stage of the integer 9/7 DWT which can be used in the CCSDS-IDC algorithm requires 12 operations per samples [2].

The following compression time are only evaluations since our software implementation of the Hadamard post-transform is not optimized. These evaluations are based on the lossy compression of an image of size 2048×2048 at 2.0 bpp on a linux PC with an Intel CPU at 1.86 GHz and 1 Go memory. With a NASA implementation of the CCSDS-IDC software, the compression takes 0.45 μs per sample. The time expected for the proposed algorithm is 0.51 μs per sample or only 13% greater than CCSDS-IDC compression time. This is an expected time based on the previous complexity analysis. For comparison, we obtained a compression time 0.56 μs per sample with Kakadu V6.0 implementation of JPEG2000. This last software is highly optimized. These computation times are given for information and may not necessarily reflect the hardware compression times and implementation issues. Indeed, an optimized implementation on a FPGA or an ASIC would differ from a software implementation.

5 Conclusion

The post-transform compression scheme has been adapted to the constraints of on-board satellite compression: solutions have been set up to decrease the complexity of the post-transform scheme and a coder which produces a fully embedded bit-stream has been adapted. To decrease the complexity, the costly best representation by Lagrangian rate-distortion minimization has been replaced by a sparsity maximization criterion. This new criterion requires less computation and can be used with a progressive coder. The post-transform dictionary has also been reduced to the Hadamard transform which can be computed by a fast algorithm using only additions, subtractions or bit-shifts. Moreover, the CCSDS-IDC algorithm has been adapted to compress the post-transformed data. It produces a fully embedded bit-stream suitable for an easy bit-rate control. In particular, the signalization information is also progressively encoded. Although the post-transform compression scheme has been reduced to its minimum complexity version, the proposed solution improves the PSNR of the transmitted images. Moreover, the quality improvement essentially concerns the wavelet blocks associated to the image edges. This property is of particular interest for further image interpretation.

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