JPEG2000 evaluation for the transmission of remote sensing images on the CCSDS packet telemetry channel

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ABSTRACT

Scientific images collected by a remote platform are preferably transmitted to the ground station in lossless compressed form. However, the data rate to be transmitted has been rapidly increasing due to the developments in sensor technology; the available downlink bandwidth has not increased accordingly, thus often imposing to resort to lossy compression.

In particular, this paper deals with the evaluation of the new JPEG2000 standard for the transmission of scientific images to the ground station. We focus on a particular type of system, namely the packet telemetry channel standardized by the CCSDS (Consultative Committee for Space Data Systems), which can be used for the transmission of both application data (e.g. images) and telecommand and control data. A performance evaluation is presented, in terms of error resilience and lossy compression performance, comparing the results achieved by JPEG2000 and the classical JPEG algorithm. The simulation of the transmission aspects, including the complete channel model, is performed by means of the TOPSIM IV simulator of communication systems.

Keywords: packet telemetry, JPEG 2000, remote sensing data

1. INTRODUCTION

The transmission of remote sensing images to ground receiving stations is well-known to be a critical issue in many systems. The main reason lies in the huge amount of data to be processed and transmitted; very often the available bandwidth is not sufficient for the transmission of all data, thus requiring to employ lossy image compression techniques in order to match the available channel capacity.

As for the transmission aspects, the CCSDS (Consultative Committee for Space Data Systems) has standardized a packet telemetry system that can be used to transmit data from a remote sensing platform to ground stations. The usefulness of a standard lies in the fact that it enables interoperability between different systems, thus allowing to share resources.

In some cases, such as transmission from deep space, the communication system must account for a very severe signal-to-noise ratio (SNR), which can be as low as 0 dB; this implies that the bit-error rate is fairly higher than usual, and imposes to use powerful error correcting codes. Still, errors are likely to be present in the received data stream. As is well-known, image coders, as well as data coders in general, are very sensitive to error in the received bitstream; a single bit error can even completely prevent from decoding an image, if it occurs in the main header of the data stream. In such scenarios, it is necessary that the employed coders are designed so as to be able to cope with corrupted data streams.

Amongst others, lossy image compression can be efficiently performed by the novel JPEG2000 image compression standard, which is currently in the publication phase. JPEG2000 has been designed so as to be as flexible as possible in order to match a lot of applications, including remote sensing. In particular, it allows to perform progressive coding from the lossy up to the lossless case, thus being very interesting for a fixed data rate system with on-the-fly bit rate control. Interestingly, the algorithm is provided with error resilience capabilities, in order to counteract the

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effect of bit errors during transmission. This is a crucial aspect, since channel codes cannot reasonably guarantee to completely avoid errors; it is hence desirable that the effect of such errors is limited by the source decoder.

In this paper we evaluate the performance of the JPEG2000 standard in the lossy compression of remote sensing images. In particular, as for the transmissive scenario we focus on the CCSDS packet telemetry standard.\(^1\) It is worth noticing that there exists a baseline approach to this problem, consisting in simply evaluating the bit-error probability, and analyzing the effect of a suitable amount of random errors in the bitstream. However, this approach does not take into account the way channel codes (and possibly interleavers) distribute errors in the bitstream. Therefore, more realistic results can be obtained by simulating the source coding and transmission system down to the physical layer, although at the expense of a larger study effort. In particular, we have adopted this latter approach, using the TOPSIM IV package to simulate the transmission system at the physical layer.

This paper is organized as follows. In Sect. 2 the CCSDS packet telemetry system is briefly reviewed, and the simulated system is described in detail, while in Sect. 3 an overview of the JPEG2000 standard is given. Results are shown and discussed in Sect. 4, while in Sect. 5 conclusions are drawn.

2. THE CCSDS PACKET TELEMETRY STANDARD

Telemetry processes enable the end-to-end transport of data sets from source application processes located on space segment to distributed user application processes located on Earth, while the telecommand processes enable data transport in opposite direction.

Full advantage of all Telemetry and Telecommand System services could be realised if data transmission is compliant with all CCSDS Recommendation; to this end, this section briefly describes the data structures characterizing the Telemetry System.

The Telemetry system includes: Packet telemetry, which defines the telemetry source packet, the source packet segmentation, and the telemetry transfer frame; the CCSDS Telemetry Channel Coding defining the standardized channel coding methods.

The CCSDS Recommendations address the five layers detailed in the following.

- **Packetisation Layer:** application data are formatted into end-to-end transportable data units called TM Source Packets.\(^2\) These data are encapsulated within a primary header which contains identification, sequence control and packet length information, and an optional trailing error control field. A TM Source Packet is the basic data unit telemetered to the user by the space platform and generally contains a meaningful quantity of related measurements from a particular source.

- **Segmentation Layer:** To provide efficient data flow control, the segmentation of large packetised transportable data units into smaller communication oriented TM Source Packets (Version 1 format) or TM Segments (Version 2 format) are used. Consequently, the TM Source Packets and/or TM Segments are of proper size for placement into the data field of the data unit of the next lower layer.

- **Transfer Frame Layer:** The TM Transfer Frame is used to reliably transport Source Packets and Segments through the Telemetry and Telecommand channel to the receiving telecommunications network. As the heart of the CCSDS Telemetry and Telecommand System, the TM Transfer Frame protocols offer a range of delivery service options. An example of such a service option is the multiplexing of TM Transfer Frames into "Virtual Channels" (VCs).

- **Channel Coding Layer:** Since a basic system requirement is the error-free delivery of the TM Transfer Frames, Telemetry and Telecommand Channel Coding is used to protect the transfer frames against Telemetry and Telecommand channel noise-induced errors. The CCSDS Recommendation for Telemetry and Telecommand Channel Coding\(^3\) includes specification of a convolutionally encoded inner channel concatenated with a Reed-Solomon (RS) block-oriented outer code. The basic data units of the CCSDS Telemetry and Telecommand Channel Coding which interface with the layer below are the channel symbols output by the convolutional encoder. These are the information bits representing one or more transfer frames as parity-protected channel symbols. The RF channel physically modulates the channel symbols into RF signal patterns interpretable as bit representations. Within the error detecting and correcting capability of the channel code chosen, errors which occur as a result of the physical transmission process may be detected and corrected by the receiving entity.
Figure 1. Block scheme of the packet telemetry modulator

- **Telemetry data encapsulation:** Telemetry source packets may be segmented and placed into the data field of Telemetry segments, which are preceded by a header. The source packets and/or the segments are placed into the data field of the Transfer Frame which is preceded by a transfer frame header. If the specified RS code is used in the channel coding scheme, the transfer frame is placed into the RS data space of the RS codeblock, and the codeblock is preceded by an attached synchronisation marker.

In this paper we focus on the “channel coding” layer, which performs the physical access to the transmission channel, and provides channel coding and modulation. The simulation results presented in Sect. 4 have been obtained employing the TOPSIM IV package, which allows the simulation of complex communication systems following a time domain approach, using the baseband equivalent signal (complex envelope). The simulated system is described in detail hereafter.

2.1. SIMULATED SYSTEM

The channel coding layer of the CCSDS packet telemetry standard can be subdivided into two subsystems, namely channel access layer and physical access layer, which are described in the following. The overall block scheme is depicted in Fig. 1.

The system performs the following operations:

- A multiplexer extracts 223 source bytes, and directs them to one out of 5 available RS (255,223) coders, which appends 32 parity symbols.

- The demultiplexer reorganizes the RS output into a serial bit sequence that feeds the inner convolutional coder with rate $\frac{1}{2}$. Hence 510 bytes are output for each 223 input bytes.

- This bit stream is then processed by a standard GMSK modulator, and transmitted (physical access layer).

The channel has been assumed AWGN, and coherent GMSK demodulation is employed.

In Fig. 2 the bit, symbol and frame error rates (BER, SER and FER respectively) of the telemetry system are reported. The curves reported in are compared with simulation results achieved using image data as the input source; the line curves represent the reference performance data, while the marks indicate the simulation results obtained by using TOPSIM. As can be seen, there is a very close agreement between the simulated and reference curves, thus validating the system model employed in the TOPSIM IV simulator. In particular, in this paper we have considered SNR values ranging from 2.1 to 2.4 dB, which are relevant values in the context of transmission from
deep space. In this case, the BER ranges from $10^{-2}$ and $10^{-4}$, thus making the source coding task very critical from the standpoint of robustness, due to the high number of errors. Of course, higher SNR values could be considered; however, it is intuitive that at high SNR the robustness of the source encoder becomes an unnecessary issue, since channel codes provide an adequate degree of robustness; hence the performance comparison between JPEG and JPEG2000 is not very significant any more.

**Figure 2.** Reference (lines) and simulated (marks) performance of the CCSDS packet telemetry system

3. **AN OVERVIEW OF JPEG2000**

JPEG 2000 is the forthcoming ISO/ITU-T standard for still image coding, and is intended to provide innovative solutions according to the new trends in multimedia technologies. JPEG 2000 will yield not only superior performance with respect to existing standards in terms of rate distortion capability and subjective quality, but also numerous additional functionalities, developed to match the needs of a large set of applications such as wireless transmission, medical imagery, digital library, e-commerce. Lossless and lossy compression, progressive transmission, encoding of very large images, robustness to the presence of bit errors and region of interest coding are some representative features of secure interest for remote sensing application.

The architecture of the JPEG 2000 is based on the well known transform based coding scheme. A biorthogonal discrete transform is first applied on the source image data; then, the transform coefficients are quantized and entropy coded; finally, the output codestream is generated.

JPEG 2000 is based on the Discrete Wavelet Transform (DWT), which is applied to rectangular partitions of the image or *tiles*. The DWT can be non reversible or reversible, this latter option making possible a truly lossless compression.

Quantization with an embedded dead-zone scalar approach is then applied independently to each subband, in such a way that all the information content is preserved in the case of reversible transform.

Each subband of the wavelet decomposition is divided into rectangular blocks (typically $64 \times 64$), or *code-blocks*, which are independently encoded with EBCOT (*Embedded Block Coding with Optimized Truncation*). EBCOT employ a bit-plane approach together with context modeling and arithmetic coding. Each coefficient bit in the current bit-plane (starting from the most significant one) is encoded in only one of three steps, and a rate distortion optimization method is used to allocate the optimal number of bits to each block. The last stage is represented by arithmetic coding with recursive probability interval subdivision of Elias coding.
The bit stream output by EBCOT is obtained from the independent embedded bit streams generated for every block; basically, it is organized as a succession of layers, each layer containing the additional contributions from each code block. The block truncation points associated with each layer are optimal in the rate distortion sense. If the bit stream is randomly truncated, the departure from optimality can be small if the number of layers is large. The final JPEG 2000 bit stream consist of a global header, followed by one or more sections corresponding to tiles. Each tile section encompasses a tile header and a layered representation of the code-blocks, organized into packets.

In order to improve the transmission performance of compressed images over channels prone to bit error and packets losses, error resilient bit stream syntax and tools have been included in the JPEG 2000 standard, using the following approaches: data partitioning and resynchronization, error detection and concealment.

The simplest error resilience tool stems from the block based encoding approach. In fact, errors in the stream are local to a single code-block, and this prevents from error propagation on the whole image. The effectiveness in term of error protection can be improved by simply decreasing the code-block dimensions, obviously at the expenses of compression inefficiency. It is worth noticing that the block coding approach does not prevent from error propagation to a larger portion of the image when errors affect critical header information. For this reason, other error resilience tools have been included both at packet level (i.e. short packet format and the introduction of resynchronization markers) and at the entropy coding level. In this latter class we can mention the context reset after each coding step, the selective arithmetic coding bypass, the arithmetic coder termination at each step, the segmentation symbols. In practice all options are based on the insertion of some break points in the stream at packet, bit-plane or binary arithmetic coding level.

In the simulations reported in Sect. 4, some error resilience tools have been used in order to improve robustness to errors. In particular, we have selected the use of resynchronization markers at packet boundaries (packet_resync option), and the termination of the arithmetic coder at each step (arith_term option). This latter is the most powerful tools, as it allows to finely monitor the integrity of the bitstream, and to selectively skip data segments upon error detection.

4. EXPERIMENTS AND RESULTS

We have simulated 100 transmissions of band 1 of a 512×512 multispectral image taken by the SPOT satellite (see the left-hand-side of Fig. 3). The image has been encoded using both the JPEG2000 standard and the JPEG standard. The target quality for the decoded images has been set to 30 dB of peak SNR (PSNR); see the right-hand-side of Fig. 3. The simulations have been carried out in such a way that the maximum achievable quality (i.e. error-free transmission) is equal to about 30 dB of PSNR in both cases. This of course leads to slightly different compression ratios for the two encoders. In the JPEG2000 case, this quality is obtained at 1 bpp, which is equivalent to transmitting about 30 CCSDS frames per image; as for JPEG, the same quality is attained at 1.35 bpp, corresponding to roughly 40 CCSDS frames per image. Moreover, as already stated in Sect. 3, the JPEG2000 decoder has been used with the packet_resync and arith_term options.

In Fig. 4, the performance of JPEG2000 is reported, at different values of channel SNR. In particular, the graphs show the percentage of images decoded at a given quality level (in terms of PSNR); the bar corresponding to PSNR = 0 counts the number of images for which the decoder has not been able to start decoding, due to errors in the main header. As can be seen in Fig. 4-a and 4-b (lowest SNR) there is a significant number of images (between 5 and 30 %) that JPEG2000 is unable to decode. At higher SNR this problem does not occur. As can be noted, JPEG2000 error resilience capabilities provide graceful degradation of system performance when the channel conditions get worse.

The same analysis has been carried out for the JPEG algorithm; the results are shown in Fig. 5. It is worth noticing that, at very low SNR (Fig. 5-a and 5-b), JPEG fails to decode most of the images (failure percentage between 60 and 100 %); at higher SNR, the performance is slightly less than that of JPEG2000. In any case, it can be seen that, due to the absence of error-resilience tools, the behaviour of JPEG is of an on/off type depending on channels conditions.

In terms of BER, these results point out that, while JPEG2000 exhibits significant robustness at BER down to 10⁻², JPEG fails if the BER is larger than 10⁻³.

In Fig. 6 the average performance of JPEG and JPEG2000 is shown, in terms of the average PSNR achieved for 100 transmissions. It can be noted that, while at high channel SNR the JPEG performance gap is moderate with
with JPEG2000, the difference at low rates is dominated by the large percentage of images not decoded by JPEG*.

As for images decoded from a corrupted bitstream, in Fig. 7 an example is provided for JPEG2000 and JPEG. As can be seen, JPEG2000 is able to considerably limit the effect of errors, in that skipping the decoding of lost packets typically yields a slight blurring effect (see left-hand-side of 7). Conversely, in the JPEG case, either decoding is stopped upon detection of an error (as in the right-hand-side of Fig. 7), or decoding proceeds blindly, propagating the effect of errors.

In summary, it can be seen from Fig. 4 and 5 that the actual benefit of using JPEG2000 rather than JPEG, lies in the fact that JPEG 2000 provides a moderate degree of quality even at very low channel SNR; asymptotically at higher SNR, the comparison results are dominated by the higher compression performance of JPEG2000, which is able to yield a more compact bitstream than JPEG, at equal quality, or less distortion at equal rate. In conclusion, it turns out that using JPEG 2000 yields a more robust system at low SNR, and higher image quality at high SNR. However, the considerably larger complexity of JPEG2000 is an issue to be carefully dealt with in the design of the on-board system.

5. CONCLUSIONS

In this paper, we have addressed the performance evaluation of the new JPEG2000 standard for the lossy compression of images transmitted from deep space using the CCSDS packet telemetry standard. In particular we have set up a complete simulator of the physical access layer and channel access layer, employing the TOPSIM IV simulator of communication systems.

Results have shown that JPEG2000 is indeed capable of improving upon the performance of the classical JPEG standard. In particular, the error-resilience tools embodied in JPEG2000 lead to very graceful performance degradation in the case of very low channel SNR, such as in the case of transmission from deep-space.

This performance improvement comes at the expense of complexity; infact, it is known* that JPEG2000 is considerably more resource-demanding than the classical JPEG algorithm. Therefore, even though the algorithm has been designed to offer functionalities desirable for space applications, such as progressive lossy-to-lossless compression, the

*These ones have been given zero value in the average PSNR computation
Figure 4. Percentage of images decoded by JPEG2000 at a given PSNR, with channel SNR of (a) 2.1 dB, (b) 2.2 dB, (c) 2.3 dB, (d) 2.4 dB

use of JPEG2000 for the on-board compression of very large images requires considerable computational capabilities, which are not always available on space platforms. On the other hand, we have shown in this paper that there undoubtedly exist advantages in using JPEG2000 in the context of transmission from deep space, due to the fact that it better guarantees the integrity, or at least the interpretability of the received data.

REFERENCES
Figure 5. Percentage of images decoded by JPEG at a given PSNR, with channel SNR of (a) 2.1 dB, (b) 2.2 dB, (c) 2.3 dB, (d) 2.4 dB.

Figure 6. Average PSNR decoded by JPEG 2000 (solid line) vs. JPEG (dashed line) as a function of channel SNR.
Figure 7. Example of decoded image from a corrupted bitstream. Left: JPEG2000 decoded band 1 of the original SPOT image; right: JPEG decoded data