Introduction to Multi Attribute Decision Making-based Application Layer Joint Coding for Image Transmission over Deep Space Channels

Igor Bisio, Fabio Lavagetto, Mario Marchese
Department of Communications, Computer and System Science
University of Genoa
Genoa, Italy
e-mail: { igor.bisio, fabio.lavagetto, mario.marchese }@unige.it

***Abstract*—The paper presents an introductive work concerning the joint application layer coding for image transmission over deep space channels. In more detail, both image compression, based on well-known algorithms (JPEG2000 and CCSDS), and encoding techniques (based on LDPC codes) to protect the sent images are simultaneously applied by the proposed joint application layer coding mechanism. It acts dynamically on the bases of the deep space channel conditions, in terms of Bit Error Rate, and it is based on the Multi-Attribute Decision Making theory. In practice, the proposal is aimed at protecting the essential informative contents of images sent through a deep space network. An introductive performance investigation of the proposal, obtained by implementing the proposed application layer joint coding scheme, is provided. The shown results are satisfactory and open the door to further developments of the proposed idea in real systems.**

Keywords-deep space communications; application layer coding; image compression; LDPC encoding; Multi-Attribute Decision Making theory.

I. INTRODUCTION

In this paper the study, implementation and performance evaluation of various communication solutions are proposed in the framework of the Deep Space Networks (DSNs).

The problems arising from the deep space environment are manifold, but it is worth highlighting that it is the hostility of this environment to require significant efforts to improve the performance of existing communication systems [1]. Nowadays, the technological advances allow connecting heterogeneous terminals separated by thousands of kilometers with satisfactory levels of quality, reliability and flexibility. Exploiting the transmission capacity of the radio channel, and recent studies on its statistical modeling is possible to achieve radio link for satellite systems (GEO, MEO and LEO) with performance levels comparable to wired-line technologies, some of which have been widely exploited in the history of the Internet over years.

Unfortunately, this may fail when the goal becomes the radio communication among devices located at distances exceeding the orbit of geostationary satellites (altitude 36.000 kilometers, with a propagation delay of radio signals that is about 125 ms) and can reach a few minutes (the distance Earth-Mars ranges between 56 and 100 million km) in the case of links with other planets.

The effects of propagation delay, noise and fluctuations of the channel status, potential jamming caused by the unexpected presence of celestial bodies become dominant and therefore necessary communication solutions may be radically different.

On the other hand, space exploration has recently taken on the surface of Mars, sophisticated analysis tools to find information on the origin of life and of the universe that could not be further exploited if there is not a possibility of transmitting to Earth's immense amount of collected information. This information often concerns images of the explored areas of the remote planets or images acquired by space probes launched to acquire information about remote celestial bodies, planets and constellations.

Considering that in deep communications system bandwidth availability, storage and computational capacity play a crucial role and represent precious, as well as limited, communications resources, highly efficient image compression algorithms, such as JPEG2000 [2] or CCSDS Image Compression Recommendation [3], may represent a key solution to optimize the resources employment.

On the other hand, due to the negative effects of deep space channels on communications to protect the image is a key issue to achieve good performance. In this case, in the recent literature it is argued that application-layer coding, obtained by applying redundancy at the application layer may be used to efficiently recover original data by guaranteeing flexibility and easy-configurability [4]. Nevertheless, the advantages of applying coding strategies at the application layer may improve the performance only in systems with low error rates [5]. In fact, high error rates imply high levels of redundancy thus causing information losses due to congestion over a DSN.

The rationale under this paper concerns the joint application of compression and redundancy: information, images in the case of this paper, is compressed and then redundancy is added. It is the concept of Application Layer Joint Coding. It allows offering the DSN a quite constant load and therefore limiting losses due to congestion. In more detail, the idea is to select, simultaneously, the best compression and coding ways on the bases of the deep space channel status as will be described in the following sections. The selection will be carried out by applying a Multi Attribute Decision Making (MADM) approach directly taken from the literature in the field [6]. The block diagram of the Application Layer Joint Coding scheme is reported in Fig. 1.

The remainder of this paper is structured as follows. Section II shortly focuses on the considered Network architecture. Image Compression Approaches (JPEG2000

978-0-7695-4067-2/10 $26.00 © 2010 IEEE
DOI 10.1109/SPACOMM.2010.21

and CCSDS) and their possible implementation (JasPer and BPE coders) are described in Section III. Section IV illustrates the employed application layer coding approach (LDPC) to protect the transmitted images. The Multi Attribute Decision Making approach to realize the joint coding and the related performance metric are introduced in Section V. An introductive performance evaluation on the proposed scheme is reported in Section VI. Then, final remarks and conclusions are drawn.

II. Deep Space Network Architecture Overview

For the sake of completeness, a brief introduction of the architecture, taken as reference in this work, has been reported. In more detail, the selected architecture, also considered in [7], is based on the Delay Tolerant Network (DTN) paradigm, which is suited to be employed in the DSNs.

A. DTN Architecture

This work takes as reference the Delay Tolerant Network architecture [8], which basically consists in the Bundle Protocol layer implemented under the application layer and running directly over transport, network or data-link layers. It fragments messages coming from the application layer into smaller units, called *bundles*. The main feature is represented by the *custodial transfer* option that allows suspending and resuming data transfer sessions. Furthermore, the availability of administrative notifications (*reports*) as well allows inferring the network state on the basis of the number of correctly received bundles.

In the architecture considered in this work, the Bundle Protocol Layer does not make use of the custodial transfer option; therefore, communication reliability has to be ensured by proper mechanisms implemented at different layers such as the Application Layer. Moreover, the Bundle Protocol acts directly over the data-link layer, which implements the Licklider Transmission Protocol (LTP), detailed in the next sub-section.

B. Licklider Transmission Protocol and Physical Layer Protocols

The Licklider Transmission Protocol (LTP) [9] is a point-to-point protocol basically implemented at the data-link layer and responsible for transferring data reliably over deep space links. It implements a recovery procedure, consisting in a Selective-ARQ strategy, which allows retransmitting all the LTP units missing packets at destination. The packets are classified into either *red* or *green* information blocks. Red blocks are usually characterized by strict reliability constraints: in case of information loss detection, selective retransmission of missing packets is performed. On the other hand, the information blocks that either 1) are tolerant to some information loss or 2) require high priority forwarding, are classified as green. In case of loss, they are not retransmitted. In this paper, only the case of red blocks is considered: in practice no packets are missed.

In general, in DSN architectures, physical layer protocols are distinguished between deep space and proximity links. The former allow data communications between nodes that are very far with each other and experience high propagation delays (several seconds). The latter are commonly established between nodes that are in proximity one with another and whose propagation delay is lower than one second.

III. Image Compression Methods

A. JPEG2000 vs CCSDS Image Compression

As previously introduced, in deep communications system bandwidth availability, storage and computational capacity play a crucial role and represent precious, as well as limited, communications resources. Starting from this consideration, high efficient image compression coding algorithms may represent a key solution to optimize the resources employment as well a way to apply successive coding, efficiently.

JPEG2000 is a wavelet-based image compression standard and coding system. It was created by the Joint Photographic Experts Group committee in the year 2000 with the intention of superseding their original discrete cosine transform-based JPEG standard. On the other hand, The Consultative Committee for Space Data Systems (CCSDS) data compression working group has adopted a recommendation for image data compression that proposes an algorithm based on a two dimensional discrete wavelet transform of the image, followed by progressive bit-plane coding of the transformed data. The algorithm can provide both lossless and lossy compression, and allows a user to directly control the compressed data volume or the fidelity with which the wavelet-transformed data can be reconstructed. CCSDS approach represents a low computational load compression and, as a consequence is suitable for both frame-based image data and scan-based sensor data, and has applications for near-earth and deep-space missions.

In this work, both JPEG2000 and CCSDS algorithms have been taken into account as reported in the performance evaluation Section of this paper.

B. JasPer vs BPE

There are several distributions that allow creating JPEG2000 encoding. JasPer is interesting for its peculiarity of being open source and can therefore exploit all the functionality of JPEG2000. In more detail, it is a software-based implementation of the codec specified in the JPEG2000 standard. The development of this software had two motivations: firstly, the developers wanted to develop a JPEG2000 implementation using the standard as only reference. Secondly, by conducting interoperability testing with other JPEG2000 implementations, developers might find ambiguities in the text of the standards, allowing them to be corrected.

In more detail, the design of the JasPer software was driven by several keys: fast execution speed, efficient memory usage, robustness, portability, modularity, maintainability, and extensibility. Since (on most platforms) fixed-point operations are typically faster than their floating-point counterparts, and since some platforms lack hardware support for floating-point operations altogether, JasPer implementers elected to use only fixed-point operations in their software to match the objectives of high portability and fast execution speed.

Concerning the implementations of the CCSDS standard, there are only two: one developed by the University of Nebraska, "BPE" and one by the Universitat Autonoma de Barcelona, the "B Software". In this paper, the first distribution, built in C + +, has been employed.

IV. APPLICATION LAYER CODING

A. *Application Layer Coding Fundamentals*

As mentioned in Section III, the briefly introduced technologies are trying to cope with the difficulties introduced by a deep space channel. For example DTNs store information in the Bundle Layers and transmit it when the channel conditions do not severely affect communications. No encoding mechanisms at the physical level are either integrated or considered [10]. In that case the idea is to apply *Forward Error Correction* (FEC) mechanisms above the bundle layer, therefore moving the complexity to the application layer, creating what in literature is called the *Application Layer Coding* [11].

The advantages of this approach are obvious: firstly, the hardware on-board must not manage complex encoding approaches, and, secondly, there is a gain in terms of flexibility: the encoding parameters changes and/or other possible reconfigurations can be achieved via software, automatically.

B. *LDPC-LDGM Coder*

The encoding technique applied in this work, coherently with the state of the art in the field, is based on a FEC approach to protect information (images) transmitted through a DSN. To accomplish this, there are many types of well-known codes, ranging from simple approaches, such as Repetition Codes, most complex ones, such as Convolutional codes or Rateless codes.

These algorithms differ in the efficiency, the ease/difficulty of implementation, the complexity of encoding but, in particular, in decoding.

Obviously, the specific choice depends on the application scenario where an encoding technique may be more appropriate to be used than the others. In the case of this paper, considering deep space channels as relatively narrow-band channels with long delays, the encoding method should be able to respond with a fast decoding and a high efficiency. For this reason LDPC-LDGM codes have been applied because, among all the mentioned algorithms, they are those that perform better. Moreover, along with Raptor Codes, the LDGM codes allow exploiting the code rate parameter that can be adaptively changed based on the deep space channel status.

V. MULTI ATTRIBUTE DECISION MAKING JOINT CODING

Fig. 1 reports the Joint Coding scheme proposed in this paper. An original image identified by I is compressed, firstly, by using JPEG2000 or CCSDS indifferently, yielding $\hat{I}_{TX}$, which is then encoded by using the LDPC-LDGM encoder. The bit per pixel (bpp) is the parameter that defines the compression level of the compressed image and the code rate (R_c) is the parameter that defines the level of redundancy applied by the LDPC-LDGM encoder. Both parameters are dynamically selected by a MADM algorithm on the bases of several performance metrics, formally defined in the following, and of the deep space channel status in terms of *Bit Error Rate* (BER). The final output of the proposed scheme is I_{TX}^{FEC} , which represents the transmitted information.

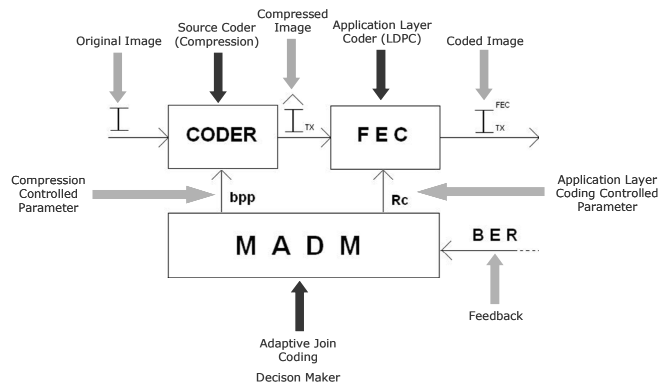

Figure 1. MADM-based Application Layer Joint Coding Scheme.

The aim of the MADM-based *Decision Maker* (DM) is to choose the best Joint Coding Pair (JCP), bpp - R_c , in order to minimize a performance vector composed of the distance between normalized measured metrics and ideal values of the same normalized metrics, defined in the reminder of the paper. From the methodological viewpoint the method has been similarly applied, in different frameworks and with different aims, in [12].

The choice is supposed to be performed when the BER value changes with respect to the previous decision. It is worth noting that, at the moment, the considered system is supposed to act "one shot". It implies that a decision performed at the beginning of the working period is valid for the overall duration of it. Further extension of this work will include the time dynamics of the deep space channels.

Considering the optimized metrics possibly in contrast each other (i.e., increasing one may imply decreasing another), the selection algorithm is based on the Multi Attribute Decision Making (MADM) [6], as previously introduced. Formally speaking: the index $k \in [1, K]$ identifies the metrics; $j \in [1, J]$ identifies each possible JCP (i.e., all combinations of the bpp - R_c parameters). One decision matrix is defined. Each element of the matrix $\hat{X}_{jk}$

is the value of the $k-th$ metric measured when the $j-th$ JPC is used. $X_{jk} = \hat{X}_{jk} / \max_j \hat{X}_{jk}$ is the normalized metric, also called attribute, over its maximum measured value. The vector containing the attributes related to the $j-th$ alternative is:

$$A_j = \left[X_{j1}, ..., X_{jk}, ..., X_{jK} \right] \quad (1)$$

The matrix $J \times K$ of the attributes for all possible J choices is:

$$\mathbf{A} = \begin{bmatrix} X_{11}, ..., X_{1k}, ..., X_{1K} \\ .... \\ X_{j1}, ..., X_{jk}, ..., X_{jK} \\ .... \\ X_{J1}, ..., X_{Jk}, ..., X_{JK} \end{bmatrix} \quad (2)$$

The selection algorithm is based on the knowledge of the ideal values, called utopia point, characterized by the ideal vector of attributes ${}^{id}A$ defined in (3).

$${}^{id}A = \left[{}^{id}X_1, ..., {}^{id}X_k, ..., {}^{id}X_K \right] \quad (3)$$

Each component of the vector is:

$${}^{id}X_k = \left\{ X_{jk} : j = \underset{j \in [1,J]}{\arg\min} X_{jk} \right\}, \forall k \in \left[1, ..., K \right] \quad (4)$$

In practice, ${}^{id}A$ is a utopia vector selecting the best value for each single attribute among all alternatives. In other words, it is the minimum value in the rows fixing the column in matrix (2).

Among the J alternatives, the JCP selection algorithm chooses the JCP called j_{opt}, which minimizes the distance, in terms of Euclidean Norm, with the ideal alternative:

$$j_{opt} = \left\{ j = \underset{j \in [1,J]}{\arg\min} \left\| A_j - {}^{id}A \right\|_2 \right\} \quad (5)$$

It allows getting the *Selection Vector* (SV) in (6).

$$SV(t) = \left[j_{opt}^1(t), ..., j_{opt}^n(t), ..., j_{opt}^N(t) \right] \quad (6)$$

The computation of the attributes for the decision is a topical point. In this paper, the measured metrics are taken at the beginning of the working period and kept constant. Attribute values $\left[X_{j1}, ..., X_{jk}, ..., X_{jK} \right]$ are collected and employed as previously described. Even if the formal approach presented above is not linked to a specific choice of attributes, the set of selected metrics for this work is:

- *Peak Signal to Noise Ratio* (PSNR) measured in dB, which is supposed computed between the ratio between I and $\hat{I}_{TX}$. It is a well-known metric used to evaluate the performance of image compression algorithms. Being related to the compression this metric is a function of the *bpp* parameter. Nevertheless the DM matrix must consider the PSNR for each bpp - R_c pair. In other words $PSNR_j(bpp, R_c)$ is the value of this attribute, valid when JCP j is applied. In short, $PSNR_j(bpp, R_c) = X_{j1}$.
- *Minimum Square Error* (MSE), which is again a well-known performance metric and, in this paper, is supposed computed between I and $\hat{I}_{RX}$, which is the compressed image received at destination transmitted through the deep space channel. This metric is a function of both *bpp* and R_c, obviously. Similarly as for the previous case: $MSE_j(bpp, R_c) = X_{j2}$.
- *Coding Time* (CT), which is the time needed to compress (by using JPEG2000 or CCSDS) and to encode (by using the LDPC encoder) a given image. In this work, it is measured by computing it for each JCP. $CT_j(bpp, R_c) = X_{j3}$.
- *Offered Load* (OL), which is the total quantity of bits that must be sent by the application layer joint coder. Also in this case, it is a function of the JCP and can be easily defined by the following quantity:

$$OF_j(bpp, R_c) = \frac{(\text{ImageWidth} \cdot \text{ImageHeight}) \cdot bpp}{R_c} \quad (7)$$

Obviously, $OL_j(bpp, R_c) = X_{j4}$.

VI. Introductive Performance Evaluation

The proposed introductive evaluation is aimed at investigating the performance obtained by using the proposed joint coding scheme by varying the transmission channel conditions (the experienced BER). The channel's effects have been considered by simulation. The proposed solution, indicated as "OPT" in the following figures, has been compared with a static approach, termed "STATIC", in which the severest compression and the most protective code rate have been applied. Both JPEG2000 (JasPer) and CCSDS (BPE) coders have been considered for the sake of completeness. In this paper just one image has been considered, identified by B3.raw in the following figures, which is a row image of size 1024 x 1024 pixel and coded with 8 *bpp*. The BER values considered are 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}. In this introductive performance evaluation, the BER acts on the bit sent from the application layer. In practice, the impact of the overall DTN functional architecture has been neglected, at the moment. The development of the proposed application layer joint coder within a complete architecture is object of ongoing research.

The considered performance metrics are the same metrics provided to the decision matrix defined in (2). In more detail, Fig. 2 and Fig. 3 show the MSE in case of employment of JPEG2000 and CCSDS compression algorithms, respectively. In both cases, for each BER value the proposed approach (OPT) allows better results with respect to the STATIC one.

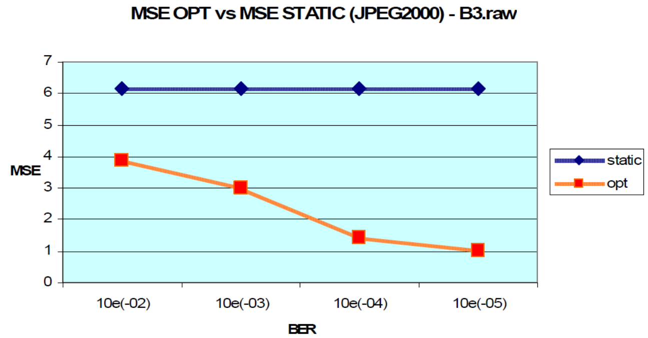

Figure 2. OPT vs STATIC – MSE Metric with JPEG2000 Image Compression.

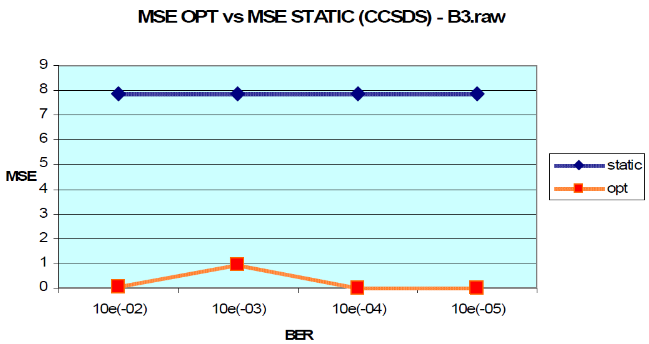

Figure 3. OPT vs STATIC – MSE Metric with CCSDS Image Compression.

The same comment can be proposed considering the PSNR (in dB) metric, whose behaviors (again for JPEG2000 and CCSDS compressors) are reported in Figures 4 and 5.

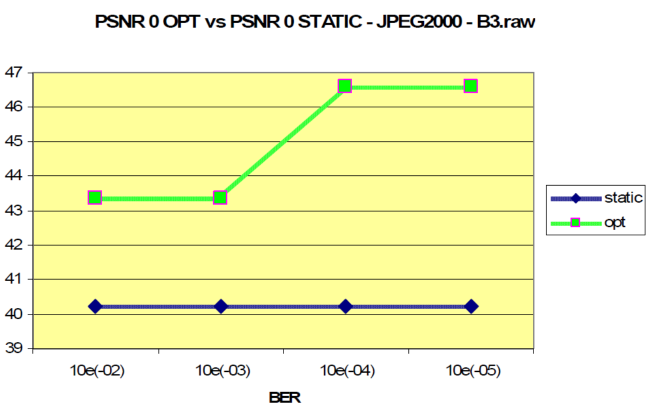

Figure 4. OPT vs STATIC – PSNR Metric with JPEG2000 Image Compression.

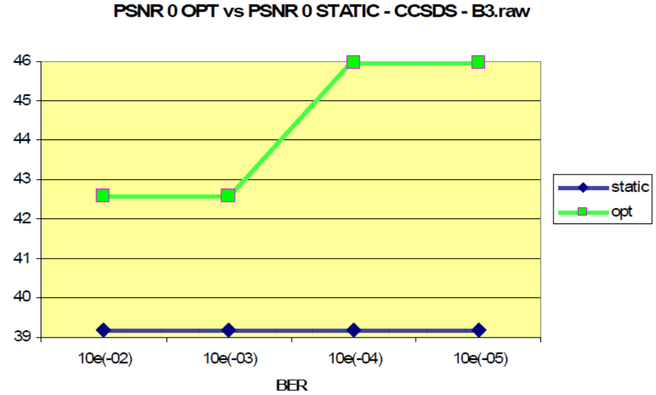

Figure 5. OPT vs STATIC – PSNR Metric with CCSDS Image Compression.

The satisfactory results concerning PSNR and MSE allow concluding that the proposed method tends to maintain a good quality of the transmitted images. This trend is the opposite if the CT (reported in [s] and called TIME in Figs. 6 and 7) and OL (measured in [bit] and called U Figs. 8 and 9) are considered. It is due to the nature of the employed decision method, based on the MADM theory, which is aimed at finding a compromise among all the considered metrics.

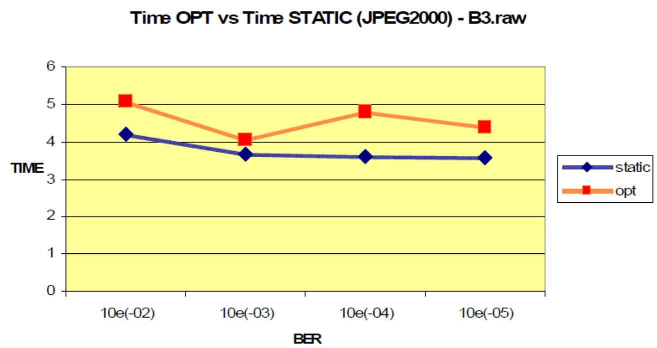

Figure 6. OPT vs STATIC – CT Metric with JPEG2000 Image Compression.

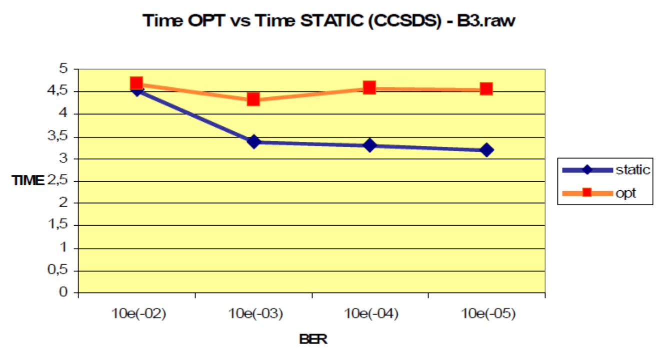

Figure 7. OPT vs STATIC – CT Metric with CCSDS Image Compression.

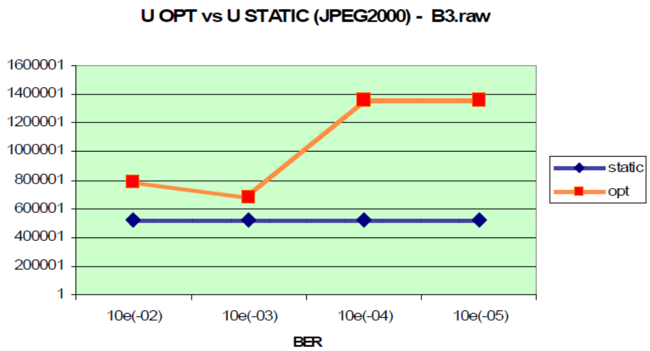

Figure 8. OPT vs STATIC – OL Metric with JPEG2000 Image Compression.

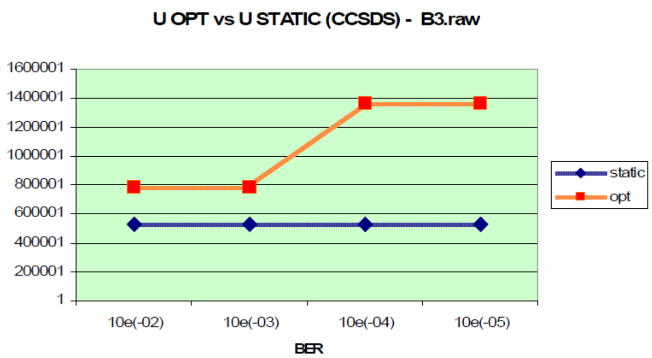

Figure 9. OPT vs STATIC – OL Metric with CCSDS Image Compression.

In general, the advantage in terms of image quality (MSE and PSNR) is paid with a limited decrease in CT and OL performances. It opens the doors to further development of the proposal in real systems.

CONCLUSIONS

The objective of this paper was the study, implementation and performance analysis of a joint application layer coding method for images based on the Multi-attribute Decision Making Theory. The proposed solution is suited to be used over interplanetary communications within the Delay-Tolerant Network architecture.

The evaluation of the proposed scheme has been accomplished via simulation. The aim was to obtain a satisfactory level of quality by protecting the sent information through coding schemes, based on LDPC encoder, and by limiting the network congestion level through compression.

The analysis allowed observing and quantifying the improvements obtained by applying the proposed solutions. The obtained results are satisfactory and allow envisaging future development of the proposed scheme aimed at applying it in real environments.

ACKNOWLEDGMENT

The authors wish to deeply thank Dr. Francesco Busdraghi for his precious support in the implementation and testing phase of this research work and for his important suggestions.

REFERENCES

[1] J. Rash, K. Hogie, and R. Casasanta, “Internet technology for future space missions,” Computer Networks, Volume 47, Issue 5, Special Issue on Interplanetary Internet, April 2005, pp. 651-659.

[2] D. S. Taubman and M. W. Marcellin, “JPEG 2000: Image Compression Fundamentals, Standards and Practice,” Kluwer International Series in Engineering and Computer Science.

[3] P. Yeh, P. Armbruster, A. Kiely, B. Masschelein, G. Moury, C. Schaefer, and C. Thiebaut, “The New CCSDS Image Compression Recommendation,” in Proc. IEEE Aerospace Conference, Big Sky, Montana, March 5-12, 2005.

[4] T. de Cola, H. Ernst, and M. Marchese, “Performance analysis of CCSDS File Delivery Protocol and erasure coding techniques in deep space environments,” Computer Networks, Volume 51, Issue 14, Oct 2007, pp. 4032-4049.

[5] Y. Choi and P. Momcilovic, “On Effectiveness of Application-layer Coding,” Proc. IEEE Infocom 2009.

[6] K. P. Yoon and C. Hwang, “Multiple Attribute Decision Making, An Introduction,” Sage University Press.

[7] I. Bisio, T. de Cola, and M. Marchese, “Congestion Aware Routing Strategies for DTN-based Interplanetary Networks,” Proc. IEEE Global Communications Conference, Globecom 2008, 30 Nov. – 4 Dec. 2008, New Orleans, LA, USA, pp. 1332-1336.

[8] K. Fall, “A Delay-Tolerant Network Architecture for Challenged Internets,” ACM SIGCOMM 2003, Karlsruhe, Germany, Aug. 2003.

[9] S. Burleigh, M. Ramadas, and S. Farrell, “Licklider Transmission Protocol - Motivation,” IRTF Internet Draft, Oct. 2007.

[10] V. Cerf, S. Burleigh, A. Hooke, L. Torgerson, R. Durst, K. Scott, K. Fall, and H. Weiss, “Delay Tolerant Network Architecture”, RFC 4838, IETF, April 2007.

[11] T. de Cola, H. Ernst, and M. Marchese, “Achieving High Goodput Performance in Mars Missions through Application Layer Coding and Transmission Power Trading,” IEEE Transactions on Circuits and Systems for Video Technology, 2007.

[12] I. Bisio and M. Marchese, “Satellite Earth Station (SES) Selection Method for Satellite-based Sensor Network,” IEEE Communications Letters, vol. 11, no. 12, December 2007, pp. 970-972.