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Application Layer Joint Coding for Image Transmission over Deep Space Channels

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***Abstract*—In this paper a method to realize the joint application layer coding for image transmission over deep space channels has been presented. In more technical detail, both image compression, based on algorithms such as JPEG2000 and CCSDS, and encoding techniques, such as LDPC codes, to protect the sent images are simultaneously applied by the proposed mechanism. It acts 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 and, at the same time, allows minimizing the load offered (the total amount of data to transmit) by the overall application layer coding process to the deep space network. The presented mechanism has been tested through simulations. The obtained results show the effectiveness of the proposal and open the door to further developments of the method in real systems.**

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

I. INTRODUCTION

The communication impairments in Deep Space Networks (DSNs) are due to the hostility of the space environment and, as a consequence, significant efforts to improve the performance of existing communication systems [1] are required. Nowadays, the technological advances allow connecting heterogeneous terminals separated by thousands of kilometers with satisfactory levels of quality, reliability and flexibility. In fact, by exploiting the transmission capacity of the radio channel, it is possible to achieve radio link for satellite systems (i.e., GEO, MEO and LEO) with performance levels comparable to wired-line technologies.

Unfortunately, this is not possible when the goal becomes the radio communication among devices located at distances exceeding the orbit of geostationary satellites (above 36.000 kilometers). In fact, propagation delay may reach a few minutes (the distance Earth-Mars ranges between 56 and 100 million km) in the case of links with other planets.

In DSNs, the effects of orbital variations of planets and satellites, delay, noise and fluctuations of the channel status, potential jamming caused by the unexpected presence of celestial bodies become dominant and therefore the necessary communication solutions may be radically different.

The importance of these solutions is clear considering that, during recent space exploration missions, sophisticated analysis tools have been deployed on the Mars surface. They are aimed at finding 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 data. This acquired information often concerns images of the explored remote planets' areas or images acquired by space probes launched to acquire information about remote celestial bodies, planets and constellations.

In deep communications system bandwidth availability, storage and computational capacity play a crucial role and represent precious, as well as limited, communications resources. As a consequence, 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 mentioned communication impairments of deep space channels, the protection of transmitted images is a key issue to achieve a good performance. The rationale under this paper is to find an opportune compromise between compression and protection: the joint coding, realized at the application layer, based on Multi Attribute Decision Making (MADM) approach.

The remainder of this paper is structured as follows: Section II revises the State of the Art in the field and highlights the paper contribution. The MADM approach to realize the joint coding and the related performance metrics are introduced in Section III. The performance evaluation of the proposed scheme is reported in Section IV. Conclusions and Future Works are drawn, finally.

II. STATE OF THE ART AND PAPER CONTRIBUTION

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.

A. Paper Concept

In more detail, in [5] the existence of two performance regions has been formally demonstrated. In a region the employment of application layer coding is significantly advantageous while it is quite useless in the second. The first performance region is represented by systems that experience low level of intrinsic loss probability. On the contrary, applying such coding in high intrinsic loss probability systems is not advantageous because the high level of necessary redundancy causes a congestion growing.

Starting from the aforementioned inspiring result, the rationale under this paper is that the boundary between the two regions can be moved so increasing the region size where the usage of the application layer coding is useful. In technical words, if the information sent from the sources is previously compressed the load offered to the network will be reduced. As a consequence, the redundancy employment does not cause a critical network load increasing.

It is the concept of Application Layer Joint Coding of this paper.

B. Specific Paper Contribution

In more technical detail, the proposed solution 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 considered image compression solutions are JPEG2000 and CCSDS Data Compression. Concerning encoding scheme, the LDPC (Low Density Parity Check) LDGM (Low Density Generator Matrix) codes have been applied.

The selection will be carried out by applying a Multi Attribute Decision Making (MADM) optimization approach directly taken from the literature in the field [6]. The proposed optimization process allows optimizing also the overall coding time and the offered load to DSN channels, simultaneously, by exploiting the features of the MADM theory and an opportune analytical definition of the metrics to optimize, proposed in the following.

III. Multi Attribute Decision Making Joint Coding

A. Application Joint Coding Scheme

An original image identified by $I(l,h)$, where the pair l,h represents each single pixel of the image, is compressed, firstly, by using JPEG2000 or CCSDS indifferently, giving $\hat{I}_{TX}(l,h)$, which is then encoded by using the LDPC-LDGM encoder. The Bit Per Pixel (δ) is the parameter that defines the compression level of the compressed image and the Code Rate (γ) 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 (shortly BER and formally ε). The final output of the proposed scheme is I_{TX}^{FEC}, which represents the transmitted information.

The aim of the MADM-based Decision Maker (DM) is to choose the best Joint Coding Vector (JCV), formally defined in the following as $\mathbf{\Omega} = [\delta, \gamma]$, in order to minimize the distance (Euclidean in the case of this work) between normalized measured metrics and ideal values of the same normalized metrics, defined below. From the methodological viewpoint the mechanism has been similarly applied, in different frameworks and with different aims, in [8].

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. A second aspect, which need to be deeply investigated in future development of this work, concern the delayed knowledge of the BER ε (the channel status in this paper) in particular in highly-delay networks such as the DSNs. Both the mentioned limits of the proposed approach will be deeply investigated in future extension of the work.

B. MADM Decision Making Entity

The key component of the proposed scheme is represented by the Decision Making Entity, whose role concerns the selection of the JCV by optimizing several performance metrics on the basis of the BER (ε) experienced by the deep space channel. 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, each metric is defined on the basis of peculiar parameters, which define a vector $\mathbf{P}_k$; $j \in [1, J]$ identifies all combinations of the δ_j - γ_j parameters, which constitute, in this work, the JCV $\mathbf{\Omega}_j$). One decision matrix is defined. Each element of the matrix $\hat{X}_{jk}(\mathbf{\Omega}_j, \mathbf{P}_k)$ is the value of the $k-th$ metric assumed when the $j-th$ JPV is used.

$$X_{jk}(\mathbf{\Omega}_j, \mathbf{P}_k) = \frac{\hat{X}_{jk}(\mathbf{\Omega}_j, \mathbf{P}_k)}{\max_{\mathbf{\Omega}_j} \hat{X}_{jk}(\mathbf{\Omega}_j, \mathbf{P}_k)} \tag{1}$$

is the normalized metric, also called attribute, over its maximum measured value. The vector containing the attributes related to the $j-th$ alternative, the JCV, is:

$$\mathbf{A}_j\left(\mathbf{\Omega}_j\right)=\left[X_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right),...,X_{jk}\left(\mathbf{\Omega}_j,\mathbf{P}_k\right),... \right.$$
$$\left. ...,X_{jK}\left(\mathbf{\Omega}_j,\mathbf{P}_K\right)\right] \quad (2)$$

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

$$\mathbf{A}=$$
$$\begin{bmatrix} X_{11}\left(\mathbf{\Omega}_1,\mathbf{P}_1\right),...,X_{1k}\left(\mathbf{\Omega}_1,\mathbf{P}_k\right),...,X_{1K}\left(\mathbf{\Omega}_1,\mathbf{P}_K\right) \\ \cdots \\ X_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right),...,X_{jk}\left(\mathbf{\Omega}_j,\mathbf{P}_k\right),...,X_{jK}\left(\mathbf{\Omega}_j,\mathbf{P}_K\right) \\ \cdots \\ X_{J1}\left(\mathbf{\Omega}_J,\mathbf{P}_1\right),...,X_{Jk}\left(\mathbf{\Omega}_J,\mathbf{P}_k\right),...,X_{JK}\left(\mathbf{\Omega}_J,\mathbf{P}_K\right) \end{bmatrix} \quad (3)$$

The selection algorithm is based on the knowledge of the ideal values, called utopia point, characterized by the ideal vector of attributes ${}^{id}\mathbf{A}$ defined in (4).

$${}^{id}\mathbf{A}=\left[{}^{id}X_1\left(\mathbf{P}_1\right),...,{}^{id}X_k\left(\mathbf{P}_k\right),...,{}^{id}X_K\left(\mathbf{P}_K\right)\right] \quad (4)$$

Each component of the vector is:

$${}^{id}X_k\left(\mathbf{P}_k\right)=\left\{X_{jk}\left(\mathbf{\Omega}_j,\mathbf{P}_k\right): \mathbf{\Omega}_j=\underset{\mathbf{\Omega}_j:j\in[1,J]}{\arg\min}\ X_{jk}\left(\mathbf{\Omega}_j,\mathbf{P}_k\right)\right\},\forall\mathbf{P}_k:k\in[1,...,K] \quad (5)$$

In practice, ${}^{id}\mathbf{A}$ is a utopia vector selecting the best value for each single attribute among all JCVs (also called alternatives). In other words, it is the minimum value in the rows fixing the column in matrix (3).

Among the J alternatives, the JCV selection algorithm chooses the JCV called $\mathbf{\Omega}_j^{opt}$, which minimizes the distance, in terms of Euclidean Norm, with the ideal alternative:

$$\mathbf{\Omega}_j^{opt}=\left\{\mathbf{\Omega}_j=\underset{\mathbf{\Omega}_j:j\in[1,J]}{\arg\min}\left\|\mathbf{A}_j\left(\mathbf{\Omega}_j\right)-{}^{id}\mathbf{A}\right\|_2\right\} \quad (6)$$

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

$$\mathbf{\Omega}_j^{opt}=\left[\delta_j^{opt},\gamma_j^{opt}\right] \quad (7)$$

The computation of the attributes for the decision is a topical point. In this paper, the metrics are computed at the beginning, before the image transmission, and supposed constant for the overall duration of the image transfer.

Attribute values $\left[X_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right),...,X_{jk}\left(\mathbf{\Omega}_j,\mathbf{P}_k\right),...,X_{jK}\left(\mathbf{\Omega}_j,\mathbf{P}_K\right)\right]$ are collected and employed as previously described.

C. Attribute Definitions

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 composed by two metrics related to image quality ($PSNR^c$ and $PSNR^t$) and two metrics due to the complexity (*CT* and *OL*) of the proposed solution. In more detail:

- *Compression Peak Signal to Noise Ratio* ($PSNR^c$) measured in dB, which is supposed computed as the ratio between $I(l,h)$ and $\hat{I}_{TX}(l,h)$. 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 δ_j parameter. Nevertheless the DM matrix must consider the $PSNR^c$ for each δ - γ pair. In other words $PSNR^c_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right)$ is the value of this attribute, valid when JCV $\mathbf{\Omega}_j$ is applied and it depends by the parameter vector $\mathbf{P}_1$. This metric is exclusively due to the employed image compression technique. In fact, given a $L\times H$ (pixels) image, the Minimum Square Error only due to compression (MSE^c_j) is:

$$MSE^c_{j1}\left(\delta_j,\mathbf{P}_1\right)=\sum_{l=0}^{L-1}\sum_{h=0}^{H-1}\left\|I(l,h)-\hat{I}_{TX}(l,h)\right\|^2 \quad (8)$$

where $\hat{I}_{TX}(l,h)$ is a function of the pair l,h (but also depends on δ, obviously) and represents each single pixel of the given image. From the aforementioned considerations, the vector $\mathbf{P}_1=[L,H]$. From MSE^c, the $PSNR^c$ attribute is defined (in dB) as

$$PSNR^c_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right)= 20\log\left(\frac{\max\limits_{\forall l\in[0,L-1];\forall h\in[0,H-1]}\left\{I(l,h)\right\}}{\sqrt{MSE^c_{j1}\left(\delta_j,\mathbf{P}_1\right)}}\right) \quad (9)$$

In short, $PSNR^c_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right)=X_{j1}\left(\mathbf{\Omega}_j,\mathbf{P}_1\right)$.

- *Total Peak Signal to Noise Ratio* ($PSNR^t$), which is analogously defined with respect to the previous, is supposed computed between $I(l,h)$ and $\hat{I}_{RX}(l,h)$, which is the compressed image received at destination transmitted through the deep space channel after FEC decoding. This metric is a function of both δ and γ, obviously. Similarly as for the previous case: $PSNR^t_{j2}\left(\mathbf{\Omega}_j,\mathbf{P}_2\right)=X_{j2}\left(\mathbf{\Omega}_j,\mathbf{P}_2\right)$. In this case, the metric depends on the used compression technique and on the channel status, in terms of BER (ε), because it considers the received image at destination:

$$MSE_{j2}^{t}\left(\mathbf{\Omega}_j,\mathbf{P}_2\right)=\sum_{l=0}^{L-1}\sum_{h=0}^{H-1}\left\|I\left(l,h\right)-\hat{I}_{RX}\left(l,h,\varepsilon\right)\right\|^2 \quad (10)$$

where the received and decoded image $\hat{I}_{RX}\left(l,h\right)$ is a function of both δ and γ; the pair l,h represents again each single pixel of the given image. As in (9) the total Peak Signal to Noise Ratio (in dB) can be written:

$$PSNR_{j2}^{t}\left(\mathbf{\Omega}_j,\mathbf{P}_2\right)= 20\log\left(\frac{\max_{\forall l\in[0,L-1];\forall h\in[0,H-1]}\left\{I\left(l,h\right)\right\}}{\sqrt{MSE_{j2}^{t}\left(\mathbf{\Omega}_j,\mathbf{P}_2\right)}}\right) \quad (11)$$

In this case the parameter vector, input of the MADM Decision Making Entity and employed in both (10) and (11), depends on the image size and also on the BER. As a consequence, the vector is defined $\mathbf{P}_2=\left(L,H,\varepsilon\right)$.

- *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 more detail, the metric is the sum of two components: the Compression Time and the Encoding Time. The Compression Time depends on the employed compression (JPEG2000 or CCSDC in this paper) and is a function of δ_j and of the total amount of data to compress. In the case of an image: the size $L\times H$ and the total number of Bit Per Pixel of the original image (Δ). In practice the Compression Time can be written as $T_j^c\left(\delta_j,\Delta,L,H\right)$. The Encoding Time is the time needed to protect, by using a FEC approach (LDPC-LDGM in this work) the compressed image. It depends on the encoder applied and it is a function of γ_j and of the total amount of data to encode. $T_j^e\left(\gamma_j,\delta_j,L,H\right)$. In practice,

$$CT_{j3}\left(\mathbf{\Omega}_j,\mathbf{P}_3\right)=T_j^c\left(\delta_j,\Delta,L,H\right)+ +T_j^e\left(\gamma_j,\delta_j,L,H\right) \quad (12)$$

In this work, it is obtained by computing it for each JCV. The parameters vector is, in the case of the third attribute, $\mathbf{P}_3=\left[\Delta,L,H\right]$. Appling the formal definition of the Sec. III.B, $CT_{j3}\left(\mathbf{\Omega}_j,\mathbf{P}_3\right)=X_{j3}\left(\mathbf{\Omega}_j,\mathbf{P}_3\right)$.

- *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 JCV and can be easily defined by the following quantity:

$$OL_{j4}\left(\mathbf{\Omega}_j,\mathbf{P}_4\right)=\frac{\delta_j}{\gamma_j}\left(L\times H\right) \quad (13)$$

Obviously, $OL_{j4}\left(\mathbf{\Omega}_j,\mathbf{P}_4\right)=X_{j4}\left(\mathbf{\Omega}_j,\mathbf{P}_4\right)$. The parameters vector is, in the case of the fourth attribute, $\mathbf{P}_4=\left[L,H\right]$. In the following Section, this metric will be reported in Kbyte (KB).

In more detail, concerning the MADM attributes, given the BER and the image to be transmitted, they are computed off-line to fulfill the decision matrix (3). It is possible due to the local nature of the considered metrics. Actually the employed MSE definition, depending on the received image, can be only estimated by considering the deep space channel as a Binary Symmetric Channel and noise sequence process *i.i.d.*.

IV. NUMERICAL RESULTS

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 tables, has been compared with a static approach, termed "*static*", in which the severest compression ($\delta=0.25$) and the most protective code rate ($\gamma=1/2$) have been applied in all channel conditions. It means that the minimum amount of necessary information is highly protected before transmission: this modality is suited to be used in case of congested and very noisy communication systems. If no adaptive coding is employed, this represents the safest choice, which has been taken as benchmark in this performance evaluation.

In this introductive performance investigation the proposed results concern the transmission of two images. In future extension of this work, the performance obtained with several images will be evaluated. The considered images are identified by b3.raw and b8.raw and available at http://cwe.ccsds.org/sls/docs/sls-dc/. They are row images of size 1024x1024 and 2048x2048, respectively, coded with 8 Bit Per Pixel. As a consequence, the overall sizes are 1048KB and 4198KB. Both JPEG2000 and CCSDS compressions have been considered for the sake of completeness. There are several distributions that allow realizing JPEG2000 and CCSDS compression. 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. Concerning the implementations of the CCSDS standard, the version developed by the University of Nebraska, "BPE", built in C++, has been employed.

Concerning the LDPC encoding, the simulation is based on coders, originally developed in C. Most the software freely available and introduced into the market is referred to the mentioned LDPC coders. All necessary steps have been developed in an embedded transmission system: the creation of the parity check matrix, the creation of the codeword, the transmission over a Binary Symmetric Channel (BSC) with different BER and the decoding. In the case of this paper, the realized embedded transmission system also includes the aforementioned compression approaches (JasPer or BPE, whose employment can be selected by the user) and the Adaptive Joint Coding MADM Entity. The implemented system, at the moment, allows selecting 4 compression modalities ($\delta = 0.25$, 0.5, 1 and 2) and 3 possible coding rates ($\gamma = 1/2$, $2/3$, $10/13$) hence 12 joint encodings are possible. The considered BER values are 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}. In the simulations, whose results are proposed in the following, the BER acts on the bit sent from the application layer. In practice, the impact of other possible layers of the employed protocol stack has been neglected, at the moment. The development of the proposed application layer joint coder in the framework of a complete architecture is object of ongoing research.

The considered performance metrics are the same metrics provided to the decision matrix defined in Sec. III.B. In more detail, Table I shows the $PSNR^c$ (in dB) 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.

TABLE I. OPT VS STATIC – $PSNR^c$ METRIC WITH JPEG2000 AND CCSDS IMAGE COMPRESSION.

***PSNR^c* Metric (dB)**								
BER	b3.raw				b8.raw			
	JPEG2000		CCSDS		JPEG2000		CCSDS	
	opt	*static*	*opt*	*static*	*opt*	*static*	*opt*	*static*
10e(-2)	43.3	40.2	42.7	39.2	42	42	41.3	41.3
10e(-3)	43.3	40.2	42.7	39.2	45.2	42	41.3	41.3
10e(-4)	46.7	40.2	46	39.2	45.2	42	41.3	41.3
10e(-5)	46.7	40.2	46	39.2	45.2	42	44.5	41.3

The same comment can be proposed considering the $PSNR^t$ metric, whose behaviors (again for JPEG2000 and CCSDS compressors) are reported in Table II.

TABLE II. OPT VS STATIC – $PSNR^t$ METRIC WITH JPEG2000 AND CCSDS IMAGE COMPRESSION.

***PSNR^t* Metric (dB)**								
BER	b3.raw				b8.raw			
	JPEG2000		CCSDS		JPEG2000		CCSDS	
	opt	*static*	*opt*	*static*	*opt*	*static*	*opt*	*static*
10e(-2)	42.1	40.2	42.7	39.2	42	42	41.3	41.3
10e(-3)	43.3	40.2	41.6	39.2	45.1	42	41.3	41.3
10e(-4)	46.7	40.2	46	39.2	45.1	42	41.3	41.3
10e(-5)	46.7	40.2	46	39.2	45.1	42	44.5	41.3

In Tables I and II, it is worth noting that the *static* approach has always the same performance independently of the channel status. It is due to the employment of the highest allowed redundancy. It allows compensating errors due to channel impairments in all considered cases (i.e., for each BER value). In practice, the $PSNR^c$ and $PSNR^t$ performance of the *static* method is exclusively due to the compression (in the former case by definition of the metric) that is always the same in all cases. The *opt* method varies its compression and encoding parameters. It explains the different behavior, obviously.

The satisfactory results concerning $PSNR^c$ and $PSNR^t$ 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] in Table III) and *OL* (measured in [KB] and reported in Table IV) 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. In general, the advantage in terms of image quality ($PSNR^c$ and $PSNR^t$) is paid with a (limited) decreasing in CT and OL performances. In these cases the highlighted behaviors may be shortly described as a decreasing trend of the CT and increasing trend of the OL for both JPEG2000 and CCSDS. It is due to the channel conditions: if they are good, it is possible to send images with low compression levels and limited redundancy. On one hand it reduces the time needed to encode the image but, simultaneously, the offered load grows because the image is only slightly compressed. It is true only in the case of the *opt* method because it changes the compression and encoding parameters on the basis of the channel status in terms of BER. The *static* method has obviously the same CT and OL performance because it applies always the same compression and encoding.

TABLE III. OPT VS STATIC – *CT* METRIC WITH JPEG2000 AND CCSDS IMAGE COMPRESSION.

***CT* Metric (s)**								
BER	b3.raw				b8.raw			
	JPEG2000		CCSDS		JPEG2000		CCSDS	
	opt	*static*	*opt*	*static*	*opt*	*static*	*opt*	*static*
10e(-2)	5	4.2	4.7	4.6	10.2	10.2	9.7	9.8
10e(-3)	4	3.8	4.3	3.4	8.2	9.2	8	8
10e(-4)	4.8	3.7	4.6	3.3	8.1	8.2	7	7.6
10e(-5)	4.4	3.6	4.5	3.2	8	8.1	15	7.5

TABLE IV. OPT VS STATIC – *OL* METRIC WITH JPEG2000 AND CCSDS IMAGE COMPRESSION.

***OL* Metric (KB)**								
BER	b3.raw				b8.raw			
	JPEG2000		CCSDS		JPEG2000		CCSDS	
	opt	*static*	*opt*	*static*	*opt*	*static*	*opt*	*static*
10e(-2)	100	67.5	100	67.5	200	250	200	250
10e(-3)	87.5	67.5	100	67.5	775	250	175	250
10e(-4)	162.5	67.5	162.5	67.5	688	250	175	250
10e(-5)	162.5	67.5	162.5	67.5	688	250	688	250

In fact, considering that the good $PSNR^c$ and $PSNR^t$ performance corresponds to higher *OL*, it can be concluded that the quality increases if more data are sent, obviously. Actually, this is true if data are also protected because, in case of noisy channels, the quality is compromised. On the other hand, if the amount of data transmitted is maximized (no compression is applied and data are encoded) the quality achieved is the best but the transmission system could be overloaded. This is the classical application layer coding approach. These considerations have been practically confirmed by the test of the following transmission conditions:

- *Absence of Coding* (*AoC*): the images (b3.raw and b8.raw) are transmitted uncompressed and unprotected.
- *Classical Coding* (*CC*): the original images are encoded with the LDPC coder and transmitted; all the mentioned coding rates have been considered ($\gamma = 1/2$, $2/3$, $10/13$);
- *Compression Only* (*CO*): the images are only compressed before transmission; all the mentioned Bit Per Pixel values have been used ($\delta = 0.25$, 0.5, 1 and 2) for both JPEG2000 and CCSDS compressions.

These transmission conditions have been evaluated, exhaustively, in terms of performance. Nevertheless, for the sake of synthesis, just the salient results have been reported and discussed in this work.

Concerning *AoC* condition, the only performance evaluated is obviously the $PSNR^t$ whose behavior is only due to BER. It ranges between 25dB in case of very severe BER and 54dB when BER is around 10^{-5}. It happens for both images (b3.raw and b8.raw). It demonstrates the necessity of encoding, in particular for severe BER. The second drawback of the *AoC* condition deals with the offered loads: they coincide with the image sizes 1048KB and 4198KB, respectively. The evaluation of *CC* approach, again, is proposed in terms of $PSNR^t$ and *OL*. Concerning the quality of the received images, this approach is outstanding: by applying $\gamma = 1/2$ and $\gamma = 2/3$ the $PSNR^t$ is infinite for each BER value. It means that the *MSE* is equal to 0. If $\gamma = 10/13$, the $PSNR^t$ ranges between 40dB (with severe BER) to 56dB (with less severe BER). Unfortunately, the drawback of the *CC* approach is the very high *OL*, whose values are reported in Table V.

TABLE V. *OL* METRIC WITH CLASSICAL CODING TRANSMISSION CONDITION.

***OL* Metric (KB)**			
Image	Code Rate		
	1/2	*2/3*	*10/13*
b3.raw	2098	1573	1363
b8.raw	8389	6292	5453

Finally, the *CO* approach is, in practice, useless: for both images, with both JPEG2000 and CCSDS compressions and for each BER value, it does not allow $PSNR^t$ values above 35dB, which practically represents the minimum quality value. Only for BER equal to 10^{-5} $PSNR^t$ assumes values around 40dB for both images.

The brief considerations about *AoC*, *CC* and *CO* further highlights the necessity of a compromise: the proposed joint coding approach represents the mentioned compromise by achieving satisfactory performance for both images (b3 and b8) in all BER conditions (Tables I, II, III, IV).

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 evaluation of the proposed scheme has been accomplished via simulation.

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

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