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Efficient Multiple Concatenated Codes With Turbo-Like Decoding for UEP Wireless Transmission of Scalable JPEG 2000 Images

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ABSTRACT Most multimedia source encoders produce scalable bit streams that are vulnerable to noisy channel effects. Unequal error protection (UEP) designs are attractive solutions for such scalable bit streams. In the other hand, the structure of multiple concatenated codes, which consist of the combination of two or more elementary encoders and interleavers, offers a flexible implementation of unequal data protection. To provide an efficient protection for embedded source bit streams, an adaptive concatenated coding/decoding design is proposed in this paper inspired by serially concatenated turbo codes. This scheme involves iterative decoding of concatenated codes for JPEG 2000 image transmission. In the case of time varying channels, the concatenated coding rates are adaptively chosen to maximize the visual quality. The simulation results show that the proposed scheme achieves better image quality improvements at the receiver side compared with a conventional multiple turbo codes-based design, with significant peak-signal-to-noise ratio gains.

INDEX TERMS Scalable bit streams, unequal error protection (UEP), multiple concatenated codes, iterative decoding, JPEG 2000.

I. INTRODUCTION

Over the past decade, the world of information technology has seen a joint development of multimedia technologies and wireless transmission systems. At the same time, there is an unprecedented development of wireless communications. In fact, the need to connect users anywhere at any time with acceptable quality has required the development of advanced multimedia coding and decoding architectures. Since source-coding technologies have reached sufficient maturity with high compression rates and good Quality of Service (QoS), the new transmission systems should now guarantee an efficient and reliable exchange of the scalable multimedia information taking into account the wireless transmission channel, generally source of degradations. Thus, new architectures of transmitters and receivers have evolved to support higher treatment rates. Therefore, an efficient error-protection scheme is needed for the transmission of scalable sources.

Unequal Error Protection (UEP) of embedded sources is a well investigated topic in the literature in which a different level of protection is applied to each part of the compressed bit streams to ensure reliable transmission of multimedia data. In [1], Cyclic Redundancy Check (CRC) codes are used with Forward Error Correction (FEC) coding to protect Set Partitioning In Hierarchical Trees (SPIHT) encoded images. Later, UEP is provided by using non-uniform channel coding throughout the bit stream in [2] and by using a Rate-Compatible Punctured Convolutional (RCPC) codes applying different channel code rates for different kinds of bits of SPIHT encoded data in [3]. Many achievements of the UEP strategy, tailored for JPEG 2000 image transmission, have been proposed [4]–[9]. In [4], an UEP scheme was presented to minimize the end to end distortion within a total transmission rate constraint over memory-less channels. Recently, [5] proposed a turbo code that provides descending protection capabilities for the data according to their locations in a block, and used this UEP strategy to JPEG 2000 image transmission to achieve better quality. In [6], a low complexity UEP scheme is designed to jointly allocate bits among source coding, channel coding and cooperation to minimize the reconstructed distortion of JPEG 2000 image transmission at the receiver. The authors of [7] introduce a technique that utilizes the channel polarization property of polar codes to achieve UEP without any significant modification within the context of JPEG 2000. In [8], a hierarchical channel coding schemes providing UEP is used for progressive quality JPEG 2000 image transmission over noisy channel. The authors of [9] proposed a novel strategy for embedding UEP into turbo codes, exclusively based on proper design of the interleaving rule. In [10], an algorithm based on dynamic programming for optimal rate allocation to provide an ideal adjustment for an unequal error protection scheme is proposed. The authors of [11] investigated the performance of optimized 2-layered and 3-layered UEP schemes using hierarchical modulation of SPIHT encoded images transmission over Additive White Gaussian Noise (AWGN) channel.

In [4], an UEP scheme was presented to minimize the end to UEP strategies have long proved their interest in the transmission of scalable sources. These can usually be obtained by using RCPC [3], [12], Reed-Solomon (RS) codes [13] or by exploiting the error protection tools defined by the JPEG 2000 standard [14]. On the other hand, UEP strategies can be also achieved by using concatenated coding schemes. These latter consist of the concatenation of two or more simple elementary encoders and interleavers. The need of a high coding gains for some applications such as deep-space applications, digital broadcasting, and many others has promoted the evolution of Concatenated Codes (CC), which became since then a standard for these applications. In the first concatenated coding scheme proposed by Forney [15], the simple concatenation of two elementary decoders was not optimal, because the internal decoder does not take advantage of the redundancy introduced by the external decoder. Thus, a new coding/decoding scheme known as turbo-codes was introduced in [16]. Turbo-codes demonstrated a correction capacity close to the theoretical Shannon capacity limits and emphasized the great potential of coding/ decoding schemes formed by concatenated encoders/decoders operating simultaneously.

The idea of parallel concatenation of two codes has been extended to multiple codes in [17]. This new established scheme is called Multiple Turbo Codes (MTC) and is built from the parallel concatenation of more than two elementary codes, which is a direct extension of the conventional turbo-codes introduced by Berrou *et al.* [16]. MTC have been investigated in a number of references [17]–[22]. The authors of [17] have shown that MTC provide a very high coding gains at low Signal-to-Noise Ratio (SNR). In particular, a low error ratio can be achieved at rates much higher than the cutoff rate of the channel. In [18], a concatenated coding scheme based on a serial concatenation of three elementary codes with two interleavers was proposed. This scheme is formed by a serial concatenation of an external encoder, an interleaver permuting the external encoder codeword bits, a middle encoder, another interleaver and an internal encoder whose inputs are the permuted middle codewords. The authors of [18] have shown that this new system offers a comparable performance, and in some cases, higher performance than that of turbo-codes with equivalent rate. In [19], the authors extend the method of designing concatenated coding schemes with EXtrinsic Information Transfer (EXIT) charts to multiple turbo codes and designed a power-efficient low-rate coding scheme. The authors of [20] investigated optimal decoding schedule of serial and parallel concatenated codes with more than two components.

Moreover, concatenated coding can also be used to provide unequal protection for embedded data stream. In this context, the authors of [23] proposed a systematic design framework for optimal low-complexity punctured multiple parallel concatenated codes. The designed algorithm is based on a grid search to find the optimal puncturing ratios and energy allocation. In [24], a concatenated coding scheme for the transmission of a scalable stream is presented. By properly adjusting the system parameters, a flexible protection strategy is achieved. An extension of this design is introduced in [25] by considering a minimum distortion variance optimization criterion.

The research community working on concatenated coding usually assumes that the used source is independent and identically distributed (iid), which is not accurate for scalable content. On the other hand, the research community that works on content-oriented coding has proposed UEP solutions but haven't yet investigated the joint source-channel iterative decoding aspect. Therefore, we propose in this work, a robust and adaptive concatenated coding/decoding design for the transmission of JPEG 2000 embedded bit streams. The proposed scheme is based on serial concatenated codes mechanism with iterative decoding offering a flexible unequal data protection strategy. Moreover, by properly adjusting the rates of the error correcting codes, an adaptive unequal error protection strategy can be obtained for the transmission of a scalable content through time-varying noisy channels. The main contributions of the proposed schemes are:

1) Unlike standard concatenated codes which use independent coding/ decoding mechanisms for each quality layer, the proposed encoder structure is based on an embedded serial concatenated coding scheme with multiplexed source data. Such a structure enable turbo-like iterative decoding and allows the different quality layers to exchange correction information.
2) Most existing schemes obtain UEP capability by optimizing several parameters (length of the codes blocks, number of information words to be encoded, ...). However, the proposed turbo UEP scheme takes advantage of the natural concatenation of elementary codes with iterative decoding to improve the performances.

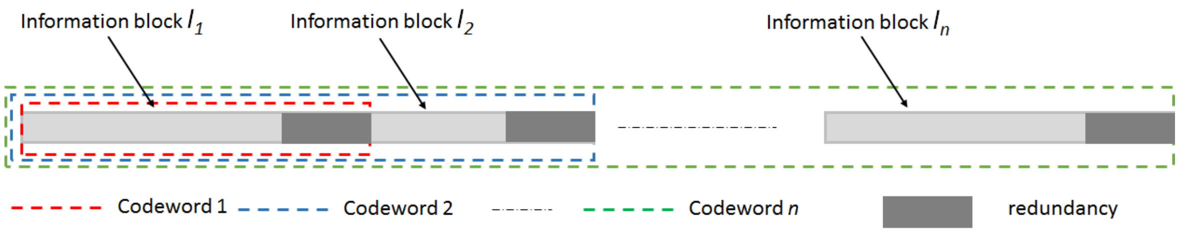


FIGURE 1. Encoding scheme using concatenated block coding [24].

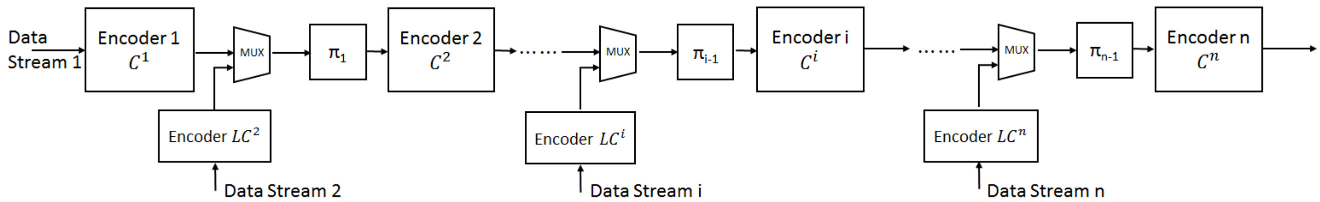


FIGURE 2. Proposed embedded serial encoding scheme for JPEG 2000 data streams.

3) The proposed scheme offers a flexible unequal data protection strategy with efficient decoding performance.

The paper is organized as follows: In Section II, a background information about concatenated codes for embedded source bit streams is briefly explained. In Section III, the proposed serial encoding/decoding scheme is presented and the algorithm design is addressed. The system performance in terms of Peak Signal to Noise Ratio (PSNR) and Bit Error Rate (BER) is also presented. We also compare the decoding strategy of the proposed design to previous coding architectures. Section IV introduces the adaptive extended system. The adaptive strategy as well as the system performance are also discussed. Finally, a brief summary and conclusion follow in Section V.

II. CONCATENATED CODING FOR EMBEDDED BIT STREAM TRANSMISSION

Concatenated block codes are considered in [24] for embedded bit stream transmission over error-prone memoryless channels. The proposed coding structure is illustrated in Fig. 1. It is based on n encoding stages, in which each codeword is concatenated with the information block I_i, $i = 1 \ldots n$, and encoded using a certain rate code after interleaving. This recursive encoding process continues until the last codeword c_n is encoded. Finally, the total bit stream is transmitted over a Binary Symmetric Channel (BSC). At the decoder, the sequential encoding operations of the encoding stage are performed in reverse order. The received noisy codeword $\hat{c}_n$ is decoded first using an ordinary Viterbi decoder. Next, the noisy codeword $\hat{c}_{n-1}$ is decoded, etc. The recursive decoding process continues until the first noisy codeword $\hat{c}_1$ is decoded.

It was demonstrated in [24] that the proposed scheme ensures decoding gains, compared to a conventional encoding scheme, by providing flexible transmission capabilities. These gains are obtained by optimizing the number of information words to be encoded, the rates of the Error Correction Codes (ECC) and the length of the codes blocks under given global rate constraint. These performances can be further improved if we consider iterative decoding. In this context, we propose in this paper a coding scheme adapted to the transmission of multimedia content and a decoding design built on the principle of turbo iterative decoding. A serial concatenation of n ($n > 2$) convolutional encoders separated by $(n-1)$ random interleavers is then considered, as well as unequal data protection for the transmission of scalable data streams is given.

III. EMBEDDED SERIAL ENCODING WITH TURBO-LIKE DECODING PROPOSED SCHEME

A. SERIAL ENCODING/DECODING SCHEME DESCRIPTION

The general concept behind the proposed coding scheme is illustrated in Fig. 2. The structure of the encoder is formed by the serial concatenation of n ($n > 2$) encoders denoted C^i with rates R_c^i, $i = 1 \ldots n$, and $n-1$ interleavers (π_i), $i = 1 \ldots n-1$, separating each pair of encoder. To ensure similar performance for the n encoded streams, we require that each stream should be encoded by at least two concatenated codes. Additional local convolutional encoders denoted LC^i, with rates R_{lc}^i, $i = 2 \ldots n$, are then added before the concatenation of each data stream except the first one. In order to ensure an encoding of higher rate codes using standard rate, a punctured convolutional code is considered in this study. Note that convolutional codes are used in this study as Soft Input Soft Output (SISO) ECCs to reduce the complexity.

To remain in a general context, the transmission of n scalable data streams denoted DS_i of length k_i, $i = 1 \ldots n$, is considered. These data streams can be considered as the quality

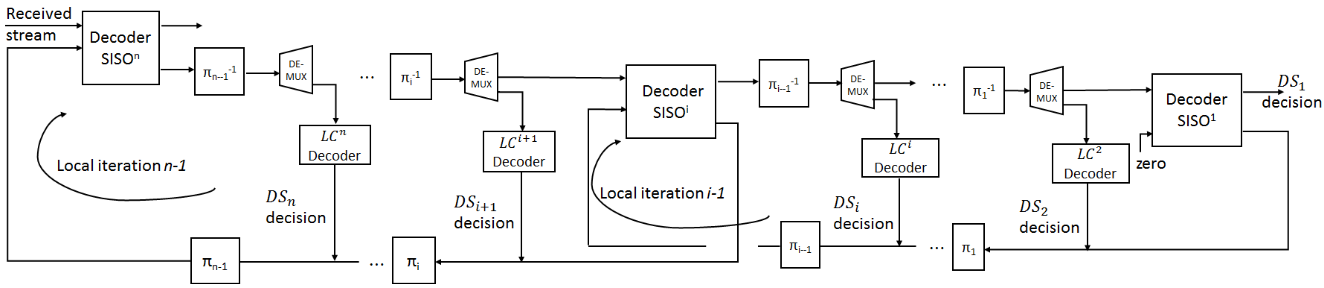


FIGURE 3. **Proposed turbo-like iterative decoding for the embedded serially concatenated encoding scheme.**

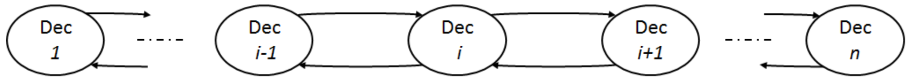


FIGURE 4. **Adopted serial message exchange decoding structure.**

layers of an encoded image using a scalable encoder. Let x_i, $i = 1 \dots n$, denote the size of the codeword at the output of the different encoders. The lengths of the codeword at the output of the different encoders are respectively equal to:

$$\begin{cases} x_1 = \dfrac{k_1}{R_c^1} \\ x_i = \dfrac{x_{i-1} + \frac{k_i}{R_{lc}^i}}{R_c^i}, \quad i = 2 \dots n. \end{cases} \tag{1}$$

The overall rate R_c of the concatenated scheme is equal to:

$$R_c = \frac{\sum_1^n k_i}{x_n}. \tag{2}$$

The proposed coding operating principle consists of the following steps. First, the data stream 1 is encoded by the first encoder (C^1). Second, the data streams i are encoded with the local encoders LC^i, for $i = 2 \dots n$. Then, the outputs of the LC^i encoders are concatenated with the outputs of the C^{i-1} encoders for $i = 2 \dots n$. Next, the concatenated streams are interleaved π_{i-1}, $i = 2 \dots n$. Finally, the C^n encoder is applied to the interleaved stream. Thus, data stream 1 is protected using n serially concatenated codes, data streams i, $i = 2 \dots n$, are protected using respectively j, $j = n \dots 2$, serially concatenated codes. The output of the last encoder (C^n) is, then, transmitted through an AWGN channel using Binary Phase Shift Keying (BPSK) modulation to ensure robustness of the transmission. Note that the transmission on a realistic channel with more complex modulations can also be used.

This new embedded stream system based on a serially concatenated encoding/decoding mechanism offers a flexible strategy for unequal data protection. The proposed scheme can be exploited for the transmission of scalable compressed images. Indeed, if the transmission of n quality layers sorted in a decreasing importance order is considered, this scheme can offer more protection to the most important layers, which would improve the quality of the received images.

The proposed decoding schemes is illustrated in Fig. 3. It is formed of $n-1$ global loops and $n-1$ local loops. A global loop is formed by two consecutive SISO decoders and a local loop is composed by a SISO decoder and a SISO LC decoder. Thus, the extrinsic information at the output of the local decoder LC^i is concatenated with the *a priori* information from the $SISO^{i-1}$ decoder. After interleaving, the new *a priori* information is fed back to the input of the $SISO^i$ decoder for $i = n \dots 2$. The decoder performs the sequential coding operations of the concatenated encoders in the reverse order. The LLR (Log-Likelihood Ratio) passing strategy used for the turbo-like iterative decoding between the n SISO decoders is inspired from the serial decoding configuration applied in [18].

In this configuration, reported in Fig. 4, each decoder passes its extrinsic information to the previous and next decoders and receives the extrinsic information from the previous and next decoders. Thus, each decoder uses the extrinsic information produced by the previous and next decoder while performing the iterative decoding. The detailed decoding algorithm is summarized in Algorithm 1.

For complexity reduction, the adopted SISO decoding algorithm for elementary codes is the Max-Log MAP algorithm [26], which is an efficient suboptimal version of the MAP algorithm.

B. PROPOSED SYSTEM SIMULATION RESULTS

This section is dedicated to the analysis of the proposed transmission strategy presented in the previous section by running Monte-Carlo simulations. The objective is to evaluate the performance of the proposed scheme in the case of JPEG 2000 encoded images transmitted across an AWGN channel. We are also interested in the information bit-error rate for different SNR in dB. A comparison of the results with a conventional multiple turbo coding/decoding scheme will also be investigated. In order to simplify the transmission scheme,

Algorithm 1 Iterative Decoding of Serially Concatenated Embedded Codes

Step 1: Initialization

Set all *a priori* information to zero.

Step 2: Iterative decoding and decision

Decoder n:

1) Decode the received sequence by the decoder $SISO^n$.
2) De-interleave (π_{n-1}^{-1}) the decoded sequence.
3) Decode the retrieved decoded data stream DS_n by the local LC^n decoder and fed back the corresponding *a priori* information to the decoder $SISO^n$.
4) Retrieve the extrinsic information of data stream $DS_{n-1,n-2,\ldots,1}$.

Decoder i, $i = n-1 \ldots 2$:

1) Decode the sequence of data at the output of decoder $SISO^{i+1}$ by the decoder $SISO^i$.
2) De-interleave (π_{i-1}^{-1}) the decoded sequence.
3) Decode the retrieved decoded data stream DS_i by the local LC^i decoder and fed back the corresponding *a priori* information to the decoder $SISO^i$.
4) Retrieve the extrinsic information of data stream $DS_{i-1,i-2,\ldots 1}$.
5) Fed back the *a priori* (π_i) information to the decoder $SISO^{i+1}$.

Decoder 1:

1) Decode the sequence of data stream DS_1 by the first SISO decoder.
2) Fed back the *a priori* information (π_1) to the second SISO decoder.

a serial concatenation of three ($n = 3$) convolutional encoders separated by two random interleavers is considered. However, the extension of our method to ($n > 3$) concatenated codes remains also possible. In the simulations, three convolutional encoders with a constraint length $\nu = 3$ and a generator polynomial defined by $g = \{07, 03\}$ are used. As in [18], we choose a non-recursive systematic encoder for the first code C^1, and a recursive systematic encoder for the second, third and additional encoders (C^i, LC^i, $i = 2, 3$). We used an AWGN channel with very low SNR (-2 dB$\leq SNR \leq$3.5 dB) to show the robustness of the proposed scheme. The maximum number of iterations was set to 4 iterations (where there is no significant gains for more than 4 iterations). We also used an open source implementation of JPEG 2000 called OpenJPEG (J2000 library). More details about the implementation are available in [27].

1) SIMULATIONS SET-UP

We consider the transmission system of Fig. 2 with $n = 3$. The gray scale test images "Lena" and "Barbara" (512×512) pixels initially encoded at 8 bits per pixels (bpp) are compressed in three quality layers by the JPEG 2000 encoder generating at its output a pixel source rate $D_s = 0.25$ bpp for "Lena" and $D_s = 0.5$ bpp for "Barbara",

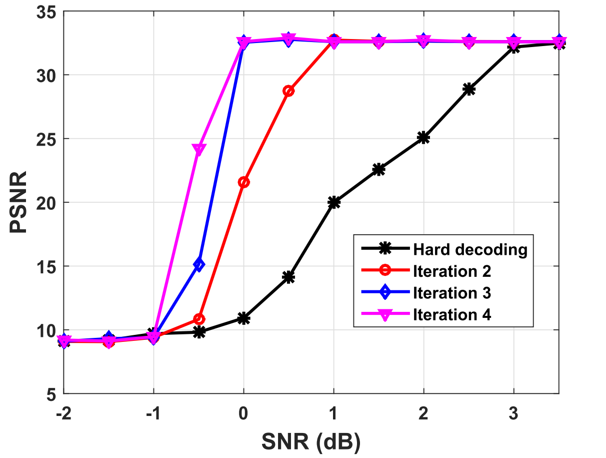


FIGURE 5. **PSNR variation for different decoding iterations, for the "Lena" image transmission through an AWGN channel with BPSK modulation. $D_s = 0.25$ bpp.**

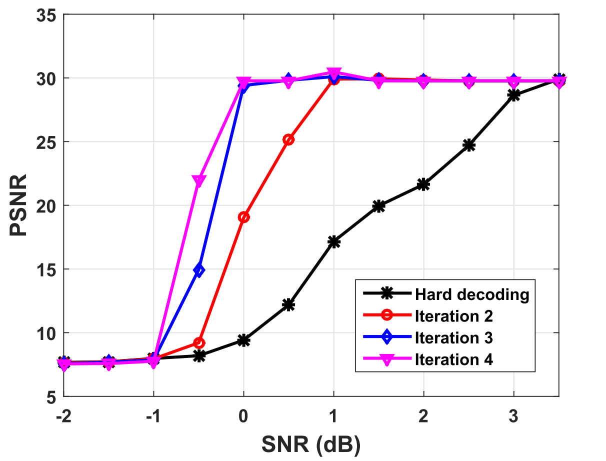
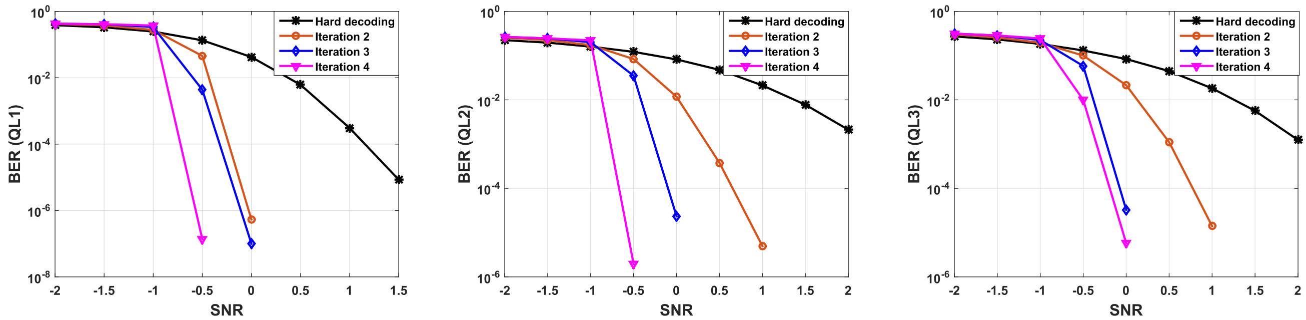


FIGURE 6. **PSNR variation for different decoding iterations, for the "Barbara" image transmission through an AWGN channel with BPSK modulation. $D_s = 0.5$ bpp.**

which correspond to a good image quality at the reception in the case of error-free transmission. With these encoding parameters, the error-free decoded picture exhibits a PSNR of 33.28 dB for "Lena" image and 31.34 dB for "Barbara" image. The quality layers are sorted in a decreasing importance order. Each quality layer is applied, according to its importance and the coding principle presented in the previous section, at the input of the corresponding convolutional encoder as described in Fig. 2. The first, second and third quality layers are applied, respectively, to the input of C^1, LC^2 and LC^3 encoders. Hence, more protection is applied to the most important quality layers. We consider the following rates $R_c^1 = 2/3, R_c^2 = 1/2, R_c^3 = 2/3, R_{lc}^2 = 1$ and $R_{lc}^3 = 1/2$, which leads to a total rate equal to $R_c = 0.28$ for "Lena" and $R_c = 0.26$ for "Barbara". To ensure similar and fair performances for the three encoded layers we require that each layer should be encoded by at least two concatenated codes, that's why we consider $R_{lc}^2 = 1$. Note that, each quality layer is partitioned into packets of $L = 8000$ bits before applying it to the corresponding encoder. The resulting



(a) (b) (c)

FIGURE 7. BER performance of the proposed iterative coding/decoding scheme. "Lena" image transmission through an AWGN channel with BPSK modulation. $D_S = 0.25$ bpp. (a) BER performance of the first quality layer. (b) BER performance of the second quality layer. (c) BER performance of the third quality layer.

(a) (b)

FIGURE 8. Examples of reconstructed images. "Lena" image, $SNR = 1$ dB. (a) Hard decoding [24]: PSNR = 22.70 dB. SSIM = 0.685. (b) Proposed approach; PSNR = 32.59 dB. SSIM = 0.874.

(a) (b)

FIGURE 9. Examples of reconstructed images. "Barbara" image, $SNR = 1$ dB. (a) Hard decoding [24]; PSNR = 19.19 dB. SSIM = 0.617. (b) Proposed approach; PSNR = 29.77 dB. SSIM = 0.794.

data stream is then transmitted through an AWGN channel by means of a BPSK modulation. Performance are evaluated in terms of PSNR averaged over 100 independent image transmissions, which is a sufficient number to evaluate the performance of the system for the specified SNRs. At the receiver, the turbo-like decoder performs iterative decoding, as described in the previous section, based on extrinsic information exchange between the three decoders in local and global iterations. For the decoding algorithm, we consider the Max-Log MAP algorithm to limit the decoding complexity.

2) SIMULATION RESULTS

Fig. 5 and Fig. 6 depict the PSNR variation provided by the proposed scheme for the "Lena" and "Barbara" images. It can be observed that the proposed iterative coding/decoding scheme provides significant gains in terms of average PSNR for more and more iterations compared to a hard-decoding scheme. This gain is essentially due to the extrinsic information exchange between the different decoders. For the "Lena" image, and for a zero SNR, an average PSNR gain of 10 dB is obtained at the second iteration compared to a hard-decoding scheme [24]. It is worth noticing that in [24] authors consider the same encoder structure (excluding the local encoder) with hard decision decoding at the receiver. This gain improves over the iterations and a gain of 11 dB is observed at the third iteration from which the system almost reach convergence. This gain is confirmed by observing Fig. 7 that represents the performance in terms of BER according to the SNR of the three quality layers. In fact, a near-error-free BER is observed at the fourth iteration for the first (Fig. 7a) and second quality layers (Fig. 7b) at $SNR > -0.5$ dB. The same BER is observed at the fourth iteration for the third quality layer (Fig. 7c) at $SNR > 0$ dB. For the "Barbara" image (Fig. 6), and for an $SNR = -0.5$ dB, an average PSNR gain of 14 dB is observed at the fourth iteration. In addition, we note a system convergence from the second iteration, for $SNR \geq 1$ dB. The good performances obtained are justified by the fact that the first layer is encoded three times and decoded by a double turbo decoder. While the second and third layers are encoded only twice and thus decoded by a single turbo decoder.

To illustrate the improvement achieved by the proposed system in terms of visual quality, we show in Fig. 8 and Fig. 9 examples of reconstructed images obtained with hard decoding and the proposed scheme for $SNR = 1$ dB. We note a clear visual quality improvement of the reconstructed image, which results in increasing the PSNR value.

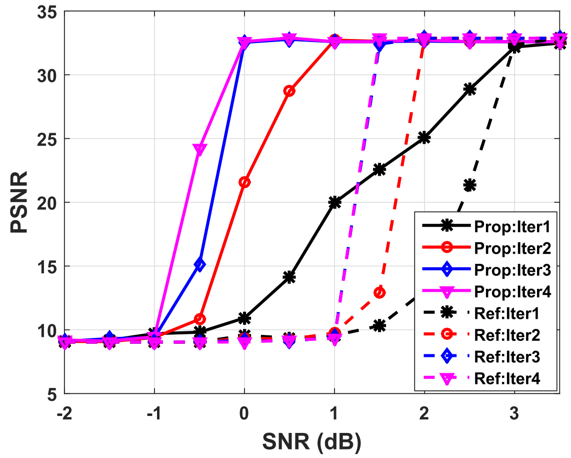


FIGURE 10. PSNR variation provided by the proposed concatenated scheme with turbo-like decoding compared to a MTC system for different decoding iterations. $D_t = 0.9$ bpp.

We now propose to compare the performances of the proposed coding/decoding scheme with a conventional multiple turbo decoding system inspired from [18], with equivalent total channel rate at the input of the channel. In the reference system, the test image "Lena" (512×512) pixels (8 bpp) is compressed using the JPEG 2000 encoder generating an output pixel source rate of $D_s = 0.23$ bpp. The compressed quality layer is encoded by the three concatenated convolutional encoders with the following rates $R_c^1 = 1/2$, $R_c^2 = 2/3$ and $R_c^3 = 3/4$, which leads to a total rate equal to $R_c = 1/4$. With these parameters, the total channel rate D_t is equal to 0.9 bpp. The resulting data stream is then transmitted through an AWGN channel using BPSK modulation. Performance is evaluated in terms of average PSNR over 100 independent image transmissions with packet lengths equal to 8000 bits. The error-free decoded picture exhibits a PSNR of 32.86 dB for "Lena" image. In order to ensure a fair comparison, we consider a total channel rate for both systems equal to $D_t = 0.9$ bpp. Thus, the same parameters used to evaluate the performance of the proposed iterative coding/decoding scheme presented earlier are considered for the comparison. Fig. 10 illustrates the PSNR variation provided by the proposed concatenated scheme compared to MTC system.

The advantages of the proposed iterative coding/decoding scheme are clearly visible. Indeed, an average PSNR gain of almost 10.5 dB is obtained, at the first iteration, compared to the reference scheme for an $SNR = 1$ dB. At the second iteration, a gain of almost 23 dB is observed compared to the reference scheme. In addition, from a zero signal-to-noise ratio, the average PSNR obtained at the third iteration is about 32 dB. However, this value is only reached by the reference system from a signal-to-noise ratio greater than 1.5 dB. Thus, it can be concluded that the proposed iterative coding and decoding technique of concatenated codes, through an unequal data protection strategy, allows to have remarkable gains compared to standard convolutional multiple turbo decoding system.

In this section, the convolutional code rates were fixed which is not accurate for time-varying channels. An adaptive rate adjustment would allow the proposed iterative coding/decoding system to reach its maximum performance. The question that could arise: How the convolutional codes rates can be chosen to have a reconstructed image with the best possible quality at the reception for a given channel state? To answer this question we will propose in the next section an adaptive rate allocation strategy for a given variable transmission channel.

IV. ADAPTIVE EMBEDDED JPEG 2000 IMAGE ENCODING FOR TIME VARYING CHANNELS

A. RATE ADJUSTMENT FOR TIME VARYING CHANNEL

In the previous section, we proposed a robust iterative concatenated encoding/decoding scheme for the transmission of JPEG 2000 scalable content. This scheme is based on a concatenated encoding mechanism that provides a flexible strategy for unequal data protection. The performance evaluation of this coding scheme has shown the interest of using an adaptive rate allocation strategy to ensure the best performances for a time varying channel. The objective of this section is then to ensure the necessary protection for each quality layer whatever the channel conditions. The concatenated coding rates (R_c^1, R_c^2, R_c^3 and R_{lc}^3) of each convolutional code in Fig. 2 with $n = 3$, are adaptively chosen, according to the channel conditions, to maximize the system performance in terms of PSNR. In that case, a more flexible protection scheme is obtained. The chosen set of codes are reported in Table 1 where we also show the total channel codes rate R_c. The different scenarios were chosen to have rates varying from 0.1 (most robust scheme) to 0.5 (least robust scheme). More than 6 scenarios can also be considered. We consider a total channel rate for all the scenarios equal to $D_t = 1$ bpp.

TABLE 1. Rate allocation scenarios.

Scenario	CC rates	Total rate R_c
1	R_c^1= 1/2, R_c^2= 1/2, R_c^3= 1/2, R_{lc}^3= 1/2	0.187
2	R_c^1= 2/3, R_c^2= 1/2, R_c^3= 1/2, R_{lc}^3= 1/2	0.214
3	R_c^1 = 2/3, R_c^2= 1/2, R_c^3= 2/3 ,R_{lc}^3= 1/2	0.282
4	R_c^1= 2/3, R_c^2= 2/3, R_c^3= 2/3 , R_{lc}^3= 1/2	0.347
5	R_c^1= 2/3, R_c^2= 3/4, R_c^3= 3/4 ,R_{lc}^3= 1/2	0.421
6	R_c^1= 3/4, R_c^2= 3/4, R_c^3= 3/4 ,R_{lc}^3= 3/4	0.506

The adaptive strategy is based on the PSNR variation provided by the proposed concatenated scheme for the different chosen scenarios at the fourth iteration. No extra improvements were noticed after this iteration. The PSNR variations are plotted in Fig. 11. According to the channel's SNR, the set of convolutional code rates are chosen, which corresponds to a set of convolutional codes (reported in Table 1), to maximize the average PSNR of the received images. For example, for an SNR between 0 and 2 ($0 < SNR < 2$) the scenario 4 will be chosen since it corresponds to a maximum average PSNR. Note that this strategy requires a closed-loop chain for channel estimation.

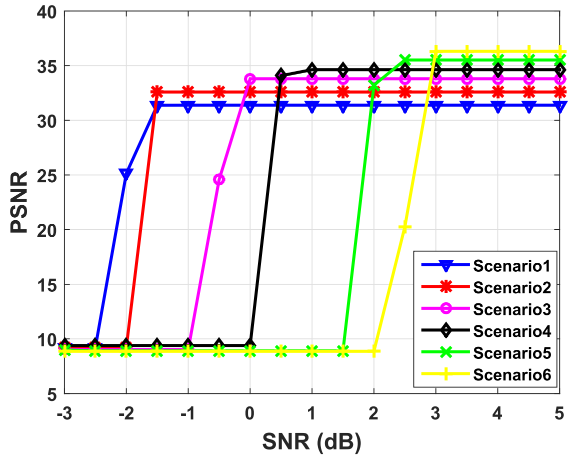


FIGURE 11. PSNR image quality as a function of SNR provided by the proposed concatenated scheme for different scenarios at the fourth iteration.

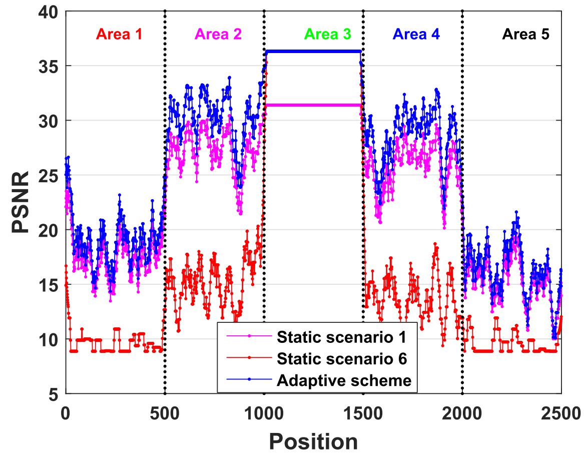


FIGURE 13. PSNR performance provided by the adaptive concatenated scheme compared to the static strategy for the "Lena" image at the fourth iteration.

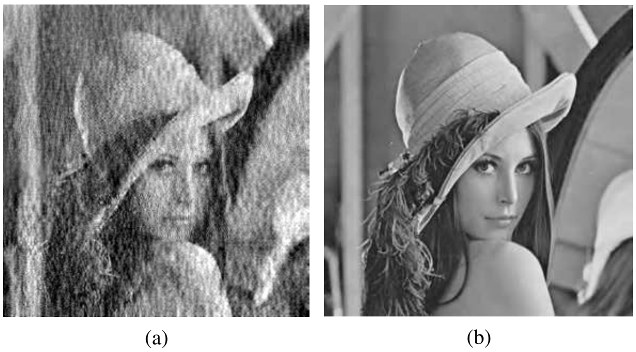


FIGURE 14. Visual comparison of reconstructed images transmitted in Area 2, position 826. (a) Static scenario 6: PSNR=18.45 dB. SSIM=0.577. (b) Adaptive strategy; PSNR=34.62 dB. SSIM=0.912.

B. PERFORMANCE EVALUATION

1) SIMULATION SET-UP

The adaptive system uses the JPEG 2000 encoder that compresses the test image "Lena" (512×512) into three hierarchical quality layers at D_s bits per pixel. Each quality layer is applied to the input of the corresponding convolutional encoder. The rates of the convolutional codes are chosen according to the SNR of the channel as described in the previous section. The encoded image is transmitted over an AWGN channel by means of a BPSK modulation. The transmission channel was simulated as if one user is moving towards a path where he experiments three transmission conditions: bad (Areas 1 and 5: $SNR < 0$ dB), average (Areas 2 and 4: 0 dB$<$ $SNR < 3$ dB) and good (Area 3: $SNR > 3$ dB). We assume that the Channel State Information (CSI) is perfectly known to the transmitter and the receiver. On the other hand, we did not investigate the effects of adaptation on delay since we are not in an optimization context.

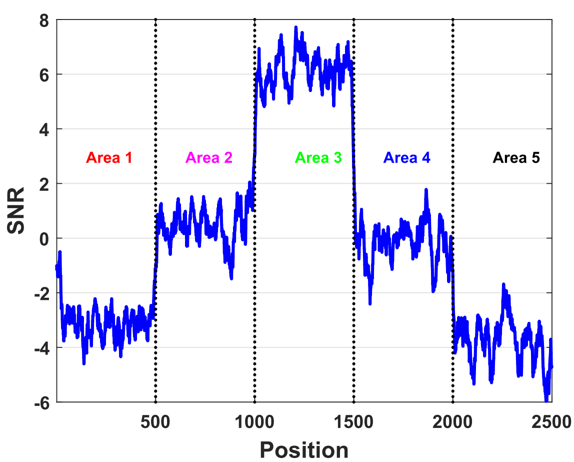


FIGURE 12. SNR evolution of the channel according to the position.

The obtained SNR evolution of the simulated channel is presented in Fig. 12. Note that each position corresponds to a different value of the SNR. We consider two reference schemes. The first corresponds to the most robust scenario and the second corresponds to the least robust scenario. Note that all curves are plotted with an equivalent total bit per pixel rate. During the simulations, the image is continuously transmitted through 2500 simulation steps. To make the curves more readable, they are averaged, using a direct dB PSNR averaging, with a sliding window containing 20 PSNR values.

2) SIMULATION RESULTS

Fig. 13 illustrates the gains reached using the adaptive strategy compared to the static strategy for the "Lena" image. It can be seen that notable gains are obtained in terms of average PSNR. This is explained by the dynamic adjustment of the concatenated coding rates that maximize the average PSNR. The static scenario 1, which corresponds to the most robust scenario, has lower performance than the adaptive strategy for the five areas. This is related to the fact that for $SNR \geq -2.5$ dB the maximum PSNR reached by this scenario is equal to 31.39 dB. On the other hand, the static scenario 6, which corresponds to the least robust scenario, shows poor performance in the case of bad and average conditions (area 1, 2, 4 and 5), and similar performance compared to the adaptive strategy for good conditions (area 3). Indeed, for $SNR \geq 3$ dB, scenario 6 is always chosen by the adaptive strategy. In the case of average conditions (area 2 and 4) the adaptive strategy exhibits a considerable coding gain of about 20 dB over the static scenario 6. The improvement is apparent when comparing the decoded images in Fig. 14.

V. CONCLUSION

In this paper, we considered the design of an embedded bit streams transmission system based on a concatenated coding/decoding mechanism. The encoder structure is based on a serial concatenated coding scheme with multiplexed source data. On the other hand, the structure of the decoder is built upon the principle of turbo iterative decoding. Thus, the proposed scheme offers a flexible unequal data protection strategy with efficient decoding performance. We have evaluated the performances of the proposed scheme, in terms of average PSNR in the context of JPEG 2000 scalable image transmission. This evaluation allowed us to observe interesting gains in terms of PSNR, which results in good visual quality. For the "Lena" image, an average PSNR gain of 10 dB is obtained at the second iteration for a zero SNR compared to a hard-decoding scheme. At the end, an adaptive rate allocation strategy has been proposed. We have showed that the adaptive strategy provides the best performances compared to the static scheme.

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