WIRELESS TRANSMISSION OF IMAGES USING JPEG2000

Nikolaos Thomos[1,3], *Nikolaos V. Boulgouris*[2], *and Michael G. Strintzis*[1,3]

[1]Information Processing Laboratory, Electrical and Computer Engineering Department,
Aristotle University of Thessaloniki, Greece
[2]The Edward S. Rogers Sr. Department of Electrical and Computer Engineering,
University of Toronto, Canada
[3]Informatics and Telematics Institute, Thessaloniki, Greece

ABSTRACT

A novel scheme is proposed for the transmission of JPEG2000 image streams over wireless channels. The proposed scheme exploits the block-based coding structure of the JPEG2000 streams and employs optimized product codes consisting of Turbo codes and Reed-Solomon codes in order to deal effectively with burst errors. The optimization is based on information extracted directly from the compressed JPEG2000 streams. Experimental evaluation demonstrates that the proposed scheme outperform other recent algorithms for the wireless transmission of images.

1. INTRODUCTION

The wide use of mobile/wireless systems in numerous everyday applications has stimulated research towards the design of suitable coding and transmission systems. The specific application of image transmission over wireless channels has deservedly attracted much attention since it requires not only careful design of the coding methodology for the compression of images, but also appropriate selection of the set of channel codes for effective forward-error-correction (FEC).

A variety of error resilient techniques [1, 2] employing product codes based on RCPC/CRC and RS codes for channel protection of SPIHT [3] streams have been recently proposed in the literature. In [4], a scheme based on Turbo-codes was presented which outperformed the method in [2] for image transmission over wireless channels. In [5] a real-time optimization algorithm was presented for the transmission of independently decodable packet streams over varying channels. The system utilizes the packetization scheme of [6]. In [7] the system of [5] was improved by combining the product code scheme of [1]. This scheme replaces the ad-hoc selection RS and RCPC codes of [1] with an EEP algorithm for fast allocation. In [8] a general framework is presented for image transmission over packet-erasure networks. The methodology in [8] takes into consideration the dependencies between information in the compressed stream in order to cluster dependent layers and protect them according to their importance.

The scheme proposed in the present paper is based on the JPEG2000 [9] source coder, which generates error-resilient streams. The source coder is used in conjunction with the application of a product code consisting of Turbo codes and Reed-Solomon codes. Due to the systematic form of Turbo codes, the immediate extraction and decoding of source information from the channel-coded stream is possible in case the stream is not corrupted. Whenever the stream is corrupted, the product codes will correct several errors. Uncorrectable errors are localized and the corrupted portion of the stream is discarded. The resulting robust transmission system is evaluated and is shown to outperform the best-performing known schemes for the transmission of images over wireless channels.

2. ERROR-RESILIENT PACKETIZATION

The JPEG2000 image coder lacks the disadvantages of the SPIHT coder. Unlike SPIHT, which uses hierarchical tree structures for the coding of wavelet coefficients, JPEG2000 is based on block coding of wavelet coefficients. The final bitstream is composed by a succession of layers which include information from independent codeblocks since their decoding does not require prior decoding of other codeblocks.

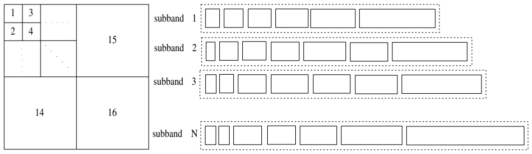


Fig. 1. Each subband forms a group of layers that can be independently protected and decoded.

One of our primary goals during the design and implementation of the system proposed in the present paper was the transmission of information in such a way so that the corrupted portion of information can be discarded without affecting the decodability of the rest of the information. For this reason, we propose the division of the wavelet coefficients to be transmitted into N disjoint sets $J_n, n = 1, \ldots, N$ in the wavelet domain so that

$$\bigcap_n J_n = \emptyset \quad \text{and} \quad \bigcup_n J_n = \mathcal{W}$$

where $\mathcal{W}$ is the set including all the coefficients of the wavelet representation. If the disjoint sets of coefficients are channel-coded

---

Email addresses: nthomos@iti.gr, nikos@comm.toronto.edu, strintzi@eng.auth.gr. This work was largely completed while the second author was with the Informatics and Telematics Institute, Thessaloniki, Greece.

0-7803-8554-3/04/$20.00 ©2004 IEEE.

appropriately into channel packets, then the erasure of a packet during transmission would not prevent the uncorrupted information from being decoded. Although numerous combinations of disjoint sets of coefficients can be conceived, in practice, since blockwise coding is performed, the subbands of the wavelet decomposition were chosen in the present paper as a reasonable compromise (see Fig. 1) between coding efficiency and information decoupling.

3. CHANNEL RATE ALLOCATION

Since the bitstreams that are generated by JPEG2000 consist of layers with unequal importance, UEP should generally be applied for their efficient protection from channel errors. The proposed UEP algorithm takes into account the importance of each packet and allocates more channel symbols (Turbo code bytes and Reed-Solomon symbols) to packets carrying important information and fewer to other packets. In this way, packets that contribute with higher distortion improvement to the eventual image quality are better protected than the rest. The problem formulated as above can be solved optimally under a specific target rate constraint by assuming that every packet includes the same number of source+channel bytes, namely R_{s+c}. Since the channel codes are variable in both horizontal and vertical direction, the beginning of the first source byte in a packet is placed immediately after the last RS symbol. On the other hand, the Turbo-code stream begins after the last source symbol. Specifically, we assume that in the n_{th} row of the product code array, there are r_n RS symbols, s_n source bytes and c_n Turbo-code bytes. The resulting product code array is schematically shown in Fig. 2.

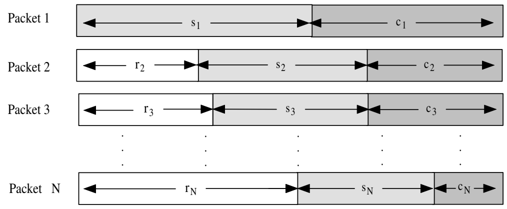


Fig. 2. Location of RS bytes, source bytes and Turbo code bytes (denoted r_n, s_n, c_n respectively) in the product-code array.

The transmission of each packet in Fig. 2 stimulates a reduction in the average (expected) distortion of the image reconstructed after transmission. Since transmitted packets are independent of each other, the eventual *distortion reduction* D is the cumulative sum of the reductions achieved by the transmission of each packet separately, *i.e.*

$$D = \sum_{n=1}^{N} Dn \tag{1}$$

where Dn is the average distortion reduction caused by the transmission of the n_{th} packet. Our intention is to determine the optimal r_n, s_n, c_n for $n = 1, \ldots, N$ by maximization of the average distortion reduction D subject to the constraint

$$r_n + s_n + c_n \leq R_p \Rightarrow s_n \leq R_p - r_n - c_n, \text{ for } n = 1, \ldots, N \tag{2}$$

where $R_p = \frac{R_{s+c}}{N}$. In order to simplify our optimization task, we make two assumptions regarding the allocation of channel rate. Since the most important subbands are placed in the first packets, we assume that the Turbo protection is non increasing with n. Similarly, we assume that the number of RS symbols in a packet is non-decreasing with n in the product code array.

The probability that the n_{th} packet is erased is denoted $p_n(c_n)$ since, for given channel conditions, it depends on the code-rate of the Turbo code that was used for its protection. Moreover, let $D_n\left(y\right)$ denote the distortion reduction achieved by the transmission of the first y *source* bytes on the n_{th} packet. $D_n\left(y\right)$ is computed for each packet based on the wavelet coefficients that are included in the packet. Note that, in practice, $D_n\left(y\right)$ is meaningful only in the interval $[0, s_n]$ or otherwise we can consider that $D_n\left(y\right) = 0$ for $y \notin [0, s_n]$.

The expected distortion depends on the number of packets that are erased during transmission. In practice, an erasure occurs when the Turbo decoder is unable to recover the information in a corrupted packet. The average distortion reduction caused by the transmission of the n_{th} packet is given by

$$Dn = \left(1 - p_n\left(c_n\right)\right) \cdot D_n\left(s_n\right) + p_n\left(c_n\right) \cdot \overline{D}_n \tag{3}$$

The term $D_n\left(s_n\right)$ in (3) expresses the distortion reduction in case of fully recovering the n_{th} packet by means of Turbo decoding, while $\overline{D}_n$ is the average distortion reduction in case the n_{th} packet is corrupted and cannot be recovered by Turbo decoding. Assume that $p_e(x)$, $x = 0, \ldots, N$ is the probability that x packets are erased. Then the average distortion reduction *in case the n_{th} packet is corrupted* is

$$\overline{D}_n = \sum_{x=1}^{N} p_e\left(x\right) \cdot D_n\left(r_{N-x+1} - r_n\right) \tag{4}$$

To gain insight regarding the term $D_n\left(r_{N-x+1} - r_n\right)$, assume that x packets are erased (see Fig. 3) during transmission. This means that only the source symbols in product code columns in which there are at least x RS symbols can be recovered. Since the level of RS protection is monotonically non-decreasing with n, the portion of the stream that can be recovered is determined by the end of the RS stream in the $N - x + 1$ packet. Thus, in every column on the left of the axis in Fig. 3, there are at least x packets carrying RS symbols which guarantee the recovery of the erased information. The probability $p_e(x)$ that exactly x packets, out of N packets in total, are erased depends on the number $t_j, j = 1, \ldots, Q$, of packets protected at the j_{th} protection level, where Q is the number of available Turbo protection levels. We define

$$u_j = \begin{cases} \min\left(t_j, x_j\right), & if \quad j = 1 \\ \min\left(t_j, x - \sum\limits_{k=1}^{j-1} x_k\right), & otherwise \end{cases} \tag{5}$$

Then

$$\begin{aligned} p_e\left(x\right) = & \sum_{x_1=0}^{u_1} \sum_{x_2=0}^{u_2} \cdots \sum_{x_{Q-1}=0}^{u_{Q-1}} p_{t_1}\left(x_1\right) \cdot p_{t_2}\left(x_2\right) \cdot \\ & \cdots \cdot p_{t_{Q-1}}\left(x_{Q-1}\right) \cdot P\left\{x_Q = x - \sum_{l=1}^{Q-1} x_l\right\} \end{aligned} \tag{6}$$

where $p_{t_j}(x_j)$ represents the probability that x_j packets are erased among the t_j packets at the j_{th} protection level.

Using (2), (3), and (4), and taking into consideration the fact that $D_n\left(r_{N+1-x} - r_n\right)$ is zero for $N + 1 - x \leq n \Rightarrow x \geq$

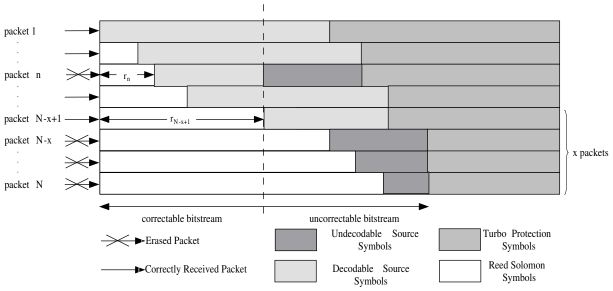


Fig. 3. When x packets are erased, the correctable portion of the bitstream lies on the left of the axis defined by the end of the RS stream in the $N - x + 1$ packet (since symbols in this stream are protected by at least x RS symbols). Information symbols that lie on the right of the axis are decodable only if they are part of uncorrupted packets.

$N + 1 - n$, eq. (1) is seen to be equal to

$$D = \sum_{n=1}^{N} \left\{ (1 - p_n(c_n)) \cdot D_n(R_p - r_n - c_n) + \right. \\ \left. + p_n(c_n) \cdot \sum_{x=1}^{N-n} (p_e(x) \cdot D_n(r_{N+1-x} - r_n)) \right\} \tag{7}$$

Note that the alteration of the RS rate r_n for the n_{th} packet produces a change in the distortion reduction of the n_{th} packet and additionally affects the distortion of other packets too. This is due to the fact that, in practice, the RS rate in a packet varies the correction capability of the RS code across all packets. Note also that the first packet does not contain any RS symbols and therefore $r_1 = 0$.

Our intention is to maximize the distortion reduction given by (7). For the efficient solution of the optimization problem, a two-stage procedure is followed: first the RS code is kept constant and the Turbo-code stream is optimized. Subsequently, the Turbo rate-allocation determined in the previous step is kept constant and the RS stream is optimized. The above procedure is repeated several times until convergence. In particular, the Turbo optimization problem is treated by exhaustive search among the allowable combinations. Since the RS rate is monotonically non-increasing with n, the RS rate-allocation problem is tackled using a fast, packet-wise bisection procedure which calculates, for the nth packet, the optimal length of the RS stream in the allowable range $[r_{n-1}, r_{n+1}]$. It should be noted that since the appropriate amounts of RS and Turbo protection are determined using a two-step process, and not jointly, the above procedure does not guarantee global optimization. In practice, however, the proposed allocation algorithm yields very satisfactory results.

4. EXPERIMENTAL RESULTS

The proposed scheme for the transmission of JPEG2000 streams over wireless channels (termed JPW) was experimentally evaluated for the transmission of the 512×512 test images "Lenna" over a flat-fading Rayleigh channel simulated using the Jakes model. Using this model, the channel is characterized by two parameters, *i.e.* the average received signal-to-noise ratio $\overline{SNR}$ and the normalized Doppler spread f_D.

Encoding	*Code Rate*	*Mean PSNR*
JPW	0.34	28.57
Sherwood [1]	0.28	27.82
Stankovic [7]	N/A	27.50

Table 1. Performance comparison for the 512×512 "Lenna" image (0.25 bpp). Mean PSNR (in dB) results are reported.

For the application of the proposed techniques, a product code consisting of 16 packets was used. In all cases a $1/3$ code rate Turbo coder was used with generator polynomials $(31, 27)$ octal. The Turbo codes were applied for the protection of symbols in the horizontal direction of the the array. The output of the Turbo coder was punctured in order to achieve higher code rates. An S-random interleaver with $S = 15$ was used with the Turbo coding/decoding processes. The maximum number of Turbo decoding iterations was 20. A CRC-16 with generator polynomial 254465 was also used for the efficient detection of corrupted packets. Each $source + channel$ packet has approximately 512 bytes. For the determination of the Turbo code-rates and the RS protection the framework of section 3 was used. In order to further improve the performance of our scheme, the approach in [10] was followed during decoding.

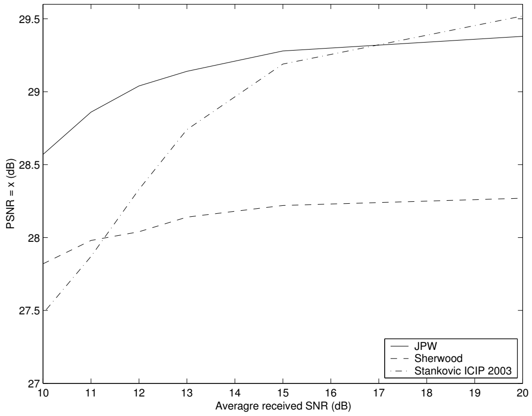


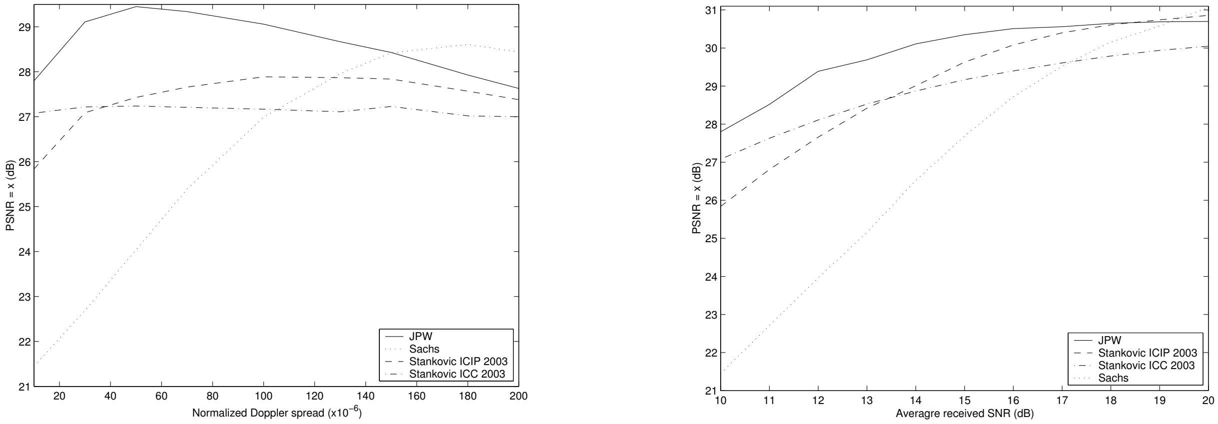
Fig. 4. Mean PSNR comparison for the transmission of the 512×512 "Lenna" image (0.25 bpp) as a function of the average SNR. The scheme was optimized for $\overline{SNR} = 10dB$ and $f_d = 10^{-5}$ and tested for various $\overline{SNRs}$ and $f_d = 10^{-5}$.

The proposed scheme was evaluated for several channel conditions. In Table 1, results are reported [1] for the case in which the design channel conditions match the actual channel conditions. As seen, our system clearly outperforms the methods in [1] and [7] by 0.75 and 1.11 dB respectively.

In Fig. 4, results are presented when optimization is performed for normalized Doppler spread $f_D = 10^{-5}$ and $\overline{SNR} = 10dB$, and transmission takes place over a wireless channel with $f_D = 10^{-5}$ and variable $\overline{SNR}$. The results show that the proposed method generally outperforms the methods presented in [1,

---

[1] A portion of the initial JPEG2000 header is assumed to be known to the decoder since it is always the same for the default coding parameters and the examined class of images.



(a) (b)

Fig. 5. Mean PSNR comparison for the transmission of the 512×512 "Lenna" image (0.25 bpp) as a function of the normalized Doppler spread f_d. The scheme was optimized for $\overline{SNR} = 13dB$ and $f_d = 10^{-4}$ and tested (a) for $\overline{SNR} = 10dB$ and various Doppler spreads. (b) for various $\overline{SNR}s$ and $f_d = 10^{-5}$.

7]. The gain over the method in [7] becomes smaller for less noisier channels since the method in [7] achieves higher noiseless PSNR. The performance gain achieved by the proposed method in comparison to the method in [1] is consistently very considerable.

In another mismatch scenario, the proposed system was optimized for normalized Doppler spread $f_D = 10^{-4}$ and $\overline{SNR} = 13dB$, and transmitted over a wireless channel with $\overline{SNR} = 10dB$ and variable f_D. Results are presented in Fig. 5(a). The comparisons are with the methods in [2, 7, 5]. The proposed UEP scheme has significantly better performance for slow-fading channels and although its performance is less impressive for fast fades, it is still superior than that in [7] and competitive to that in [2].

Finally, our scheme was evaluated for transmission over a wireless channel with $f_D = 10^{-5}$ and variable $\overline{SNR}$, when the optimization conditions were, as previously, $f_D = 10^{-5}$ and $\overline{SNR} = 13dB$. As seen in Fig. 5(b), when the channel conditions are good (high average received SNR) all methods appear to have equivalent performance. For the much more practical case of low SNRs, the present method demonstrates significant performance improvement over the other schemes in the comparison, i.e. outperforms the methods in [7, 5] by almost 0.7 dB, while the method in [2] collapses.

5. CONCLUSIONS

A novel method was proposed for the communication of JPEG2000 images over wireless channels. The proposed scheme exploits the block-based structure of the JPEG2000 streams and employs product codes consisting of Turbo codes and erasure-correction codes in order to deal effectively with burst errors. A framework for the optimal unequal error protection was also proposed. Experimental evaluation showed the superiority of the proposed scheme in comparison to well-known wireless transmission schemes.

6. ACKNOWLEDGMENT

We would like to thank Dr. Vladimir Stankovic and Dr. Rauf Hamzaoui for providing the results presented in [7].

7. REFERENCES

[1] G. Sherwood and K. Zeger, "Error Protection for Progressive Image Transmission Over Memoryless and Fading Channels," *IEEE Trans. Communications*, vol. 46, no. 12, pp. 1555–1559, Dec. 1998.

[2] D. G. Sachs, A. Raghavan, and K. Ramchandran, "Wireless image transmission using multiple-description based concatenated codes," in *Data Compression Conference*, 2000.

[3] A. Said and W. A. Pearlman, "A New Fast and Efficient Image Codec Based on Set Partitioning in Hierarchical Trees," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 6, pp. 243–250, June 1996.

[4] N. Thomos, N. V. Boulgouris, and M. G. Strintzis, "Wireless Image Transmission Using Turbo Codes and Optimal Unequal Error Protection," in *Proc. IEEE Int. Conference on Image Processing*, Barcelona, Spain, Sep. 2003.

[5] V. Stankovic, R. Hamzaoui, and Z. Xiong, "Fast formard error protection algorithms for transmission of packetized multimedia bitstreams over varying channels," in *Proc. IEEE Int. Conference on Communication*, Anchorage, AK, May 2003.

[6] X. Wu, S. Cheng, and Z. Xiong, "On packetization of embedded multimedia bitstreams.," *IEEE Trans. Multimedia*, vol. 3, no. 1, pp. 132–140, Mar. 2001.

[7] V. Stankovic, R. Hamzaoui, and Z. Xiong, "Product code error protection of packetized multimedia bitstreams," in *Proc. IEEE Int. Conference on Image Processing*, Barcelona, Spain, Sep. 2003.

[8] J. Thie and D. Taubman, "Optimal erasure protection assignment for scalable compressed data with small packets and short channel codewords," *EURASIP Journal on Applied Signal Processing*, Feb. 2004.

[9] D. S. Taubman and M. Marcellin, *JPEG2000: Image Compression Fundamentals, Standards, and Practice*, Kluwer, 2001.

[10] L. Cao and C. W. Cheng, "A novel product coding and recurrent alternate decoding scheme for image transmission over noisy channels.," *IEEE Trans. Communications*, vol. 51, no. 9, pp. 1426–1431, Sep. 2003.