

Optimal JPWL Forward Error Correction rate allocation for robust JPEG 2000 images and video streaming over Mobile Ad-hoc Networks

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ABSTRACT

Based on the analysis of real Mobile Ad-hoc Network (MANET) traces, we derive in this paper an optimal wireless JPEG 2000 compliant Forward Error Correction (FEC) rate allocation scheme for a robust streaming of images and videos over MANET. The packet based proposed scheme has a low complexity and is compliant to JPWL, the 11th part of the JPEG 2000 standard. The effectiveness of the proposed method is evaluated using a wireless Motion JPEG 2000 client/server application and the ability of the optimal scheme to guarantee Quality of Service (QoS) to wireless clients is demonstrated.

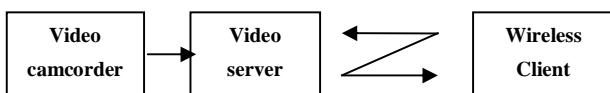
Keywords

Forward Error Correction (FEC), Unequal Error Protection (UEP), Reed-Solomon codes, wireless JPEG 2000 (JPWL), wireless video streaming, Mobile Ad-hoc Networks (MANET)

1. INTRODUCTION

Nowadays, there is an increasing demand of multimedia applications which integrate wireless transmission functionalities. Wireless networks are suitable for those types of applications, due to their ease of deployment and because they yield tremendous advantages in terms of mobility of User Equipment (UE). However, wireless networks are subject to a high level of transmission errors because they rely on radio waves whose characteristics are highly dependent of the transmission environment.

In wireless video streaming applications like the one considered in this paper (Figure 1), effective data protection is a crucial issue.



802.11 ad-hoc network

Figure 1. Wireless video streaming system

JPEG 2000, the newest image representation standard completing the existing JPEG standard [1], addresses this issue. Part 1 of this standard defines several tools allowing the decoder to detect errors in the transmitted codestream, and to re-synchronise the decoding in order to avoid erroneous decoding and crashes. Even if these tools give a first level of protection from transmission errors, they become ineffective when the transmission channel experiences high bit error rate. To overcome this limitation, Wireless JPEG 2000 (JPWL, JPEG 2000 11th part) defines techniques to increase the resilience of the codestream to transmission errors in wireless systems. JPWL specifies error resilience tools such as Forward Error Correction, interleaving and Unequal Error Protection.

In [2], the description of the JPWL system is presented and the performance of its Error Protection Block (EPB) is evaluated. A fully JPEG 2000 Part 1 compliant backward compatible error protection scheme is proposed in [3]. A memoryless Binary Symmetric Channel (BSC) is used for simulations both in [2] and [3]. However, as packets errors mainly occur in bursts, the channel model considered in those works is not realistic. Moreover JPEG 2000 codestream interleaving is not considered in [3].

In this paper we present a wireless JPEG 2000 images/video streaming system based on the recommendations of JPWL final draft [4]. To the best of our knowledge the present work is the first to rely on an analysis of real 802.11 data traces and to derive an optimal JPWL compliant FEC rate allocation method for robust JPEG 2000 images/video streaming over wireless channel. It is worth noting that the performance of this method is evaluated using a Motion JPEG 2000 video streaming application over real MANET channel traces.

The paper is arranged as follows. In section 2, the proposed JPWL based system is described. Section 3 is dedicated to the analysis and modelling of real MANET channel traces. In section 4, the FEC rate allocation problem is formalised, and an optimal FEC rate allocation method is proposed. In section 5, experimental results are derived from JPEG 2000 frames transmission over wireless channel traces. Finally, some conclusions are provided in section 6.

2. A WIRELESS JPEG 2000 IMAGES/VIDEO STREAMING SYSTEM

2.1 System Functionalities

The functionalities of the proposed JPWL based system are presented in Figure 2. The aim of this system is to efficiently transmit a Motion JPEG 2000 (MJ2) video sequence through MANET channel traces.

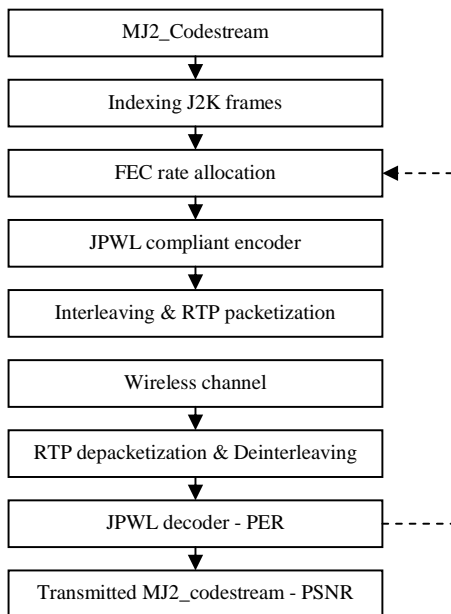


Figure 2. JPWL based system functionalities

The system is described as follows:

The input of the JPWL codec is a Motion JPEG 2000 (MJ2) file. The JPEG 2000 codestreams included in the MJ2 file are extracted and indexed.

These indexed codestreams are transmitted to the JPWL encoder ([4] presents a more accurate description of the used JPWL encoder) which applies FEC at the specified rate and adds the JPWL markers in order to make the codestream compliant to Wireless JPEG 2000 standard. At this stage, frames are still JPEG 2000 part 1 compliant, which means that any JPEG 2000 decoder is able to decode them.

To increase JPWL frames robustness, an interleaving mechanism is processed before each frame transmission through the error-prone channel. This is a recommended mechanism for transmission over wireless channel where errors occur in burst (contiguous long sequence of errors). Thanks to interleaving the correlation between error sequences is reduced.

The interleaving step is followed by RTP packetization. In this process, JPEG 2000 codestream data and other types of data are integrated into RTP packets as described in [5].

RTP packets are then transmitted through the wireless channel which is modelled in this work by a Gilbert channel model. This channel model will be further presented in section 3.2.

At the decoder side, after depacketization, the JPWL decoder corrects and decodes the received JPWL codestreams and rebuilds the JPEG 2000 frames. At this stage, parameters such as Packet Error Rate (*PER*) are extracted, increasing the knowledge of the channel state. The decoder sends extracted parameters back to the JPWL encoder via the Up link.

The last process of the transmission chain is the evaluation of the Peak Signal to Noise Ratio (PSNR) which measures the distortion between the transmitted and the decoded image/video.

2.2 JPEG 2000 codestreams transmission over the proposed JPWL system

Figure 3 presents the structure of JPEG 2000 codestreams when transmitted through our proposed JPWL system.

After the indexation of the Motion JPEG 2000 file, the original JPEG 2000 codestreams are introduced in the system. Then, our FEC rate allocation scheme selects the optimal Reed-Solomon codes and calculates the resulting JPWL protection headers. In Figure 3 this step corresponds to the JPWL protection, where redundant data are added to original codestreams. Protected data are then interleaved in order to reduce the impact of transmission errors (Interleaving Process). A detailed description of the interleaving process is presented in Section 5.1. Interleaved data are then RTP packetized (Figure 3). In this work we do not assume a particular RTP packetization scheme. It is worth noticing, that S. Futemma and al proposed in [6] an RTP payload format for JPEG 2000 streams. This work under progress defines an intelligent JPEG 2000 packets fragmentation into RTP payload for robust images/video streaming. An interesting extension to our work could be to integrate this new RTP packetization scheme in our proposed system. In our system we do not emphasize a cross-layer approach meaning that channel errors are handled at lower layers and are not transmitted to upper layers. Thus, only correctly received data packets are transmitted to the application layer.

RTP packets are transmitted through a wireless channel subject to losses (in Figure 3, packet 8 is corrupted). At the receiver side, RTP packets are depacketized and the extracted data are deinterleaved. At the following step (JPWL correction), redundant data are used to correct the corrupted part of the codestream. After JPWL correction, the transmitted codestreams are recovered and can be compared to the original codestreams.

As a better knowledge of the characteristic of the wireless channel can significantly improve the design of the FEC rate allocation mechanism, we dedicate the following section to the analysis and modeling of real MANET channel traces.

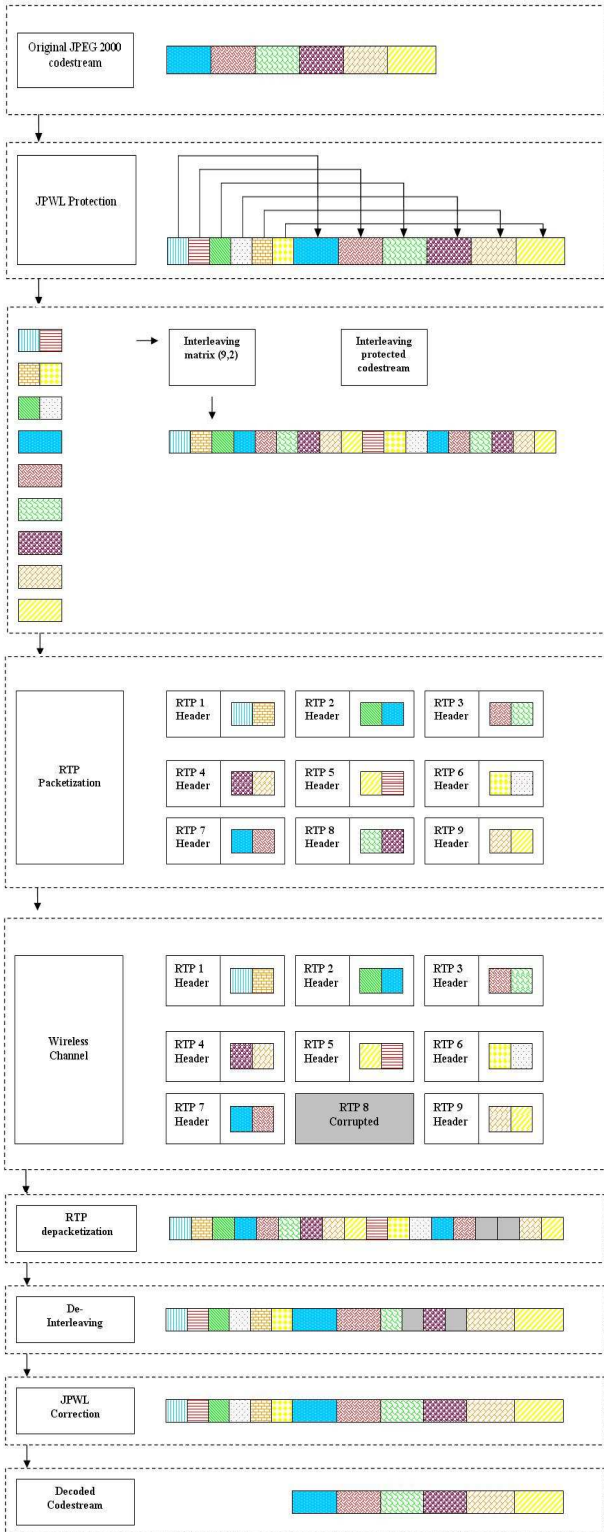


Figure 3. JPEG 2000 codestreams transmission through the proposed JPWL system

3. ANALYSING AND MODELING MANET CHANNEL TRACES

In this section we analyze loss patterns of a mobile ad-hoc network channel and derive application level models to emulate transmission error occurrences in the considered system. We first describe the loss pattern generation scenario and then focus our study on modeling these patterns with Gilbert model based on first order Markov chains.

The interest of this section is to derive conclusions on accurate transmission error modeling at application level. The generated models allow refinement of error protection strategies.

3.1 MANET loss patterns generation

The platform used to generate the loss patterns is presented in Figure 4. It consists of a client/server software pair running on two Windows XP laptops connected in ad-hoc network using two PCMCIA IEEE 802.11 b/g cards (at 2,4 GHz). As the platform only contains two laptops, no collision occur with other stations.



Figure 4. Loss patterns generation platform

The set of generated loss patterns covers different transmission scenarios (mobile or static). Each pattern corresponds to a specific Carrier to Noise ratio $\frac{C}{N}$ ($\frac{C}{N}$ is the ratio between the desired signal and the total received noise power).

The mode used at the physical layer of the wireless link is the mode 4 where the modulation is QPSK. The coding rate is 3/4 and the Nominal Data Rate $R_{Nominal}$ is 18Mbit/s. In the considered loss patterns, $\frac{C}{N}$ varies between 20 dB and 11 dB which

corresponds to a Packet Error Rate ranging from $5.1 \cdot 10^{-3}$ to $2.662 \cdot 10^{-1}$. Generated traces are available in [7].

3.2 Modeling loss patterns with Gilbert model

3.2.1 Gilbert model

The Gilbert model was first introduced by Gilbert in [8]. Elliot proposes an extension of the Gilbert model in [9], the last model is commonly known as Gilbert-Elliot (GE). In GE model, the modelled wireless channel has two states: good and bad. In the good state (g), the channel provides a constant and low error probability (P_G) whereas in the bad state (b), the channel experiences a high error probability (P_B). Hence we have $P_G \ll P_B$ for GE, $P_G = 0$ and $P_B = 1$ for the Gilbert channel. In other words Gilbert model is a simplified GE model.

In this work, we use an 8-bit symbol oriented Gilbert model to emulate the correlated error characteristics of wireless channel. Therefore, our wireless channel is modelled as a two state Markov process (Figure 5).

With this model, the channel produces error bursts because when in bad state, the probability of staying in this state is greater than the probability of returning to good state.

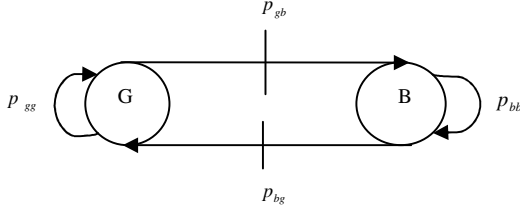


Figure 5. Two-state Markov process scheme

In Markov chains with finite state space, the transition probability distribution can be represented by a matrix called transition matrix P . The $(i, j)^{i\text{eme}}$ element of P is $P(X_{n+1} = j / X_n = i)$ with $i, j \in \{0,1\}$. Hence the transition matrix of the model presented in Figure 5 is:

$$P = \begin{bmatrix} p_{gg} & p_{gb} \\ p_{bg} & p_{bb} \end{bmatrix} = \begin{bmatrix} p_{gg} & 1 - p_{bb} \\ 1 - p_{gg} & p_{bb} \end{bmatrix}$$

From P we derive the stationary distribution $\pi = [\pi_G \ \pi_B]$ which satisfies the condition $\pi \cdot P = \pi$:

$$\begin{cases} \pi_G = \frac{1 - p_{bb}}{1 - p_{bb} + 1 - p_{gg}} \\ \pi_B = \frac{1 - p_{gg}}{1 - p_{bb} + 1 - p_{gg}} \end{cases} \quad (3-1)$$

Let L_G and L_B be respectively the mean length of error free and erroneous sequences, we have:

$$L_G = \frac{1}{1 - p_{gg}} \quad \text{and} \quad L_B = \frac{1}{1 - p_{bb}}$$

Applying Markov process at symbol level, the Symbol Error Rate (SER) for GE:

$$SER = P_G \pi_G + P_B \pi_B = \frac{P_G (1 - p_{bb}) + P_B (1 - p_{gg})}{(1 - p_{bb} + 1 - p_{gg})} \quad (3-2)$$

For the Gilbert model, we have $P_G = 0$ and $P_B = 1$, so the SER is

$$\text{given by: } SER = \frac{1 - p_{gg}}{1 - p_{bb} + 1 - p_{gg}} \quad (3-3)$$

A comprehensive description of Markov based wireless channel modelling is available in [10].

3.2.2 Traces analysis under Gilbert framework

It is worth noting that in the considered traces, each RTP packet has a fixed length of 1128 symbols (bytes). Hence, in our case the Symbol Error Rate (SER) is equal to the Packet Error Rate (PER). Therefore, packet oriented Gilbert models derived from our traces have the same characteristics and same parameters as the 8-bit symbol oriented Gilbert models used to emulate the wireless channel at application level. As loss patterns are applied on RTP packets, we present a packet oriented analysis of the traces.

In the loss patterns Good state (G) and bad state (B) are represented respectively by 0 and 1. Hence 0 corresponds to a well received RTP packet and 1 to an erroneous packet.

The distribution of error burst length is presented in Figure 6 for different loss patterns.

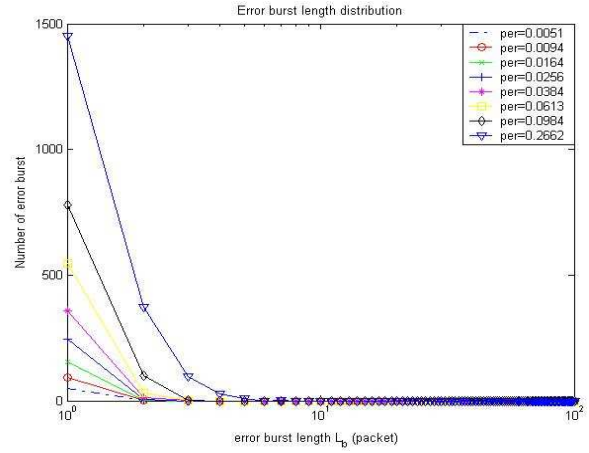


Figure 6. Error bursts distribution

From Figure 6 we notice that the error burst length is often less than 10 packets. So we consider $L_B^{\max} = 10$ as the upper bound of the error burst length.

By evaluating the error free burst length distribution in Figure 7 we show that the upper bound $L_G^{\max} = 100$ is ten time higher than the error burst length upper bound. This is due to the fact that despite in case where the wireless channel experiences fading (burst of errors), the transmission is often successful.

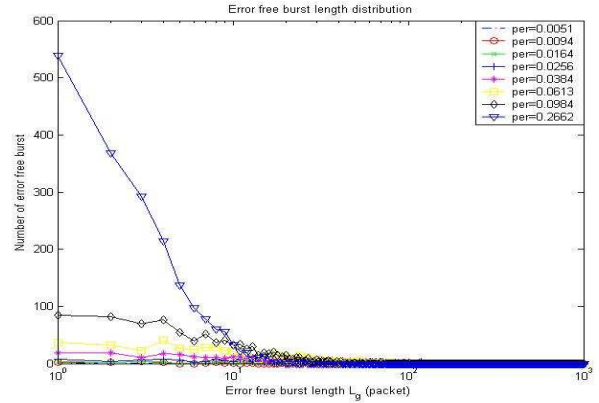


Figure 7. Error free burst length distribution

The number of error free bursts is lower than the number of error bursts, but this gap is compensated by the time spent in error free state (error free burst length) which is much longer than the one in error state (error burst length). So in our models, the mean time in the good state G should be sensibly greater than the mean time in the bad state B.

We rely on this analysis to derive accurate Gilbert model parameters p_{gb} and p_{bg} using the relation verified by R. Jain [11]:

$$p_{gb} = \frac{1}{L_G} \text{ and } p_{bg} = \frac{1}{L_B} \quad (3-4)$$

This analysis allows a better characterization of transmission errors, improving by the way the design of the FEC rate allocation scheme.

4. OPTIMAL FORWARD ERROR CORRECTION RATE ALLOCATION

Making an analogy between the FEC rate allocation problem and the Multiple-Choice Knapsack Problem (MCKP) leads to the conclusion that both problems are NP-hard. Hence, most of the algorithms proposed in the literature such as the one presented by N. Thomos and al in [12], lead to exhaustive search among different FEC rate solutions, exponentially increasing their complexity. These algorithms are thus interesting for an offline video streaming but are unpractical for real-time applications.

To overcome this limitation, Z. Guo and al proposed in [13] a slightly complex layered unequal error protection scheme for robust Motion JPEG 2000 streaming over wireless network. However, this algorithm is not JPWL compliant and was designed based on the assumption that the channel is a memoryless Binary Symmetric Channel (uncorrelated error occurrence) which is not realistic because wireless channels have correlated errors sequence. Hence, we have proposed in [14] a dynamic layered based unequal error protection FEC rate allocation methodology for efficient JPEG 2000 streaming over MANET. The proposed scheme improved the performance by about 10% compared to a priori selection of channel coding. However the main drawback of both methodologies is that the FEC rate allocation is suboptimal. In fact, in both schemes the protection strategy is layer based which implies that a selected FEC rate is applied to all the substreams belonging to the same layer. This limits the effectiveness of those protection strategies especially for fast varying channels where the selected FEC rate may need to be updated from one substream to another.

In this paper we propose a slightly complex, packet based optimal FEC rate allocation algorithm for robust Motion JPEG 2000 video streaming over wireless channel.

In subsection 4.1 we formalise the FEC rate allocation problem and introduce in subsection 4.2 the initial incremental reduction of distortion (RD_i^0) associated to the decoding of packet i . This metric is of central importance in our scheme and is derived from the JPEG 2000 encoding scheme. Subsection 4.3 introduces evaluation of the decoding error probability when using t-error correcting Reed-Solomon codes to protect JPEG 2000 codestreams.

We then present the proposed optimal FEC allocation algorithm in section 4.4.

4.1 Problem formalization

The goal is to optimally protect JPEG 2000 images/video for robust streaming over wireless channel.

Considering that JPEG 2000 codestreams are constituted by a set of S substreams, the optimal FEC allocation problem can be resumed by answering the question: How to optimally protect each substream so as to minimize the transmitted image distortion under a rate constraint determined by the available bandwidth in the system?

Since the JPEG 2000 standard specifies that packets are byte aligned, it is especially interesting to work with Galois Field $GF(2^8)$ to provide error correction capabilities. In this context, JPWL final draft [4] recommends the use of Reed-Solomon (RS) codes as FEC codes and fixes a set of RS default codes for substream protection before transmission over wireless channels.

Let γ be a substream protection level selected in the range $0 \leq \gamma \leq \gamma_{\max}$, each protection level corresponds to a specific RS code selected between JPWL default RS codes ($\gamma = 0$ means that the substream is not transmitted, $\gamma = 1$ means transmission with protection level 1, higher values imply increasing channel code capacity with γ).

Let B_{av} the byte budget constraint corresponding to the available bandwidth in the system.

Let l_i the length in bytes of the i^{th} packet of the S substreams and $RS(n, k)$ the Reed-Solomon code used for its protection, the corresponding protection level is γ and the FEC coding rate is $R = \frac{k}{n}$. We define $fec = \frac{1}{R_i} = \frac{n}{k}$ as the invert of the channel coding rate, so $l_i * fec$ represents, in byte, the increase of the i^{th} packet length when protected at level γ .

The correct decoding of packet i at the receiver yields a reduction of the distortion on the transmitted image. Let RD_i^0 be respectively the reduction of distortion associated to decoding of packet i and $RD_{i,\gamma}$ the reduction of distortion achieved when packet i is protected at level γ ($RD_{i,\gamma}$ will be further formalised). We define the gain as the ratio between the image quality improvement $RD_{i,\gamma}$ and the associated cost in terms of bandwidth consumption $l_i \times fec$.

Thus, the FEC allocation problem becomes: How to optimally select substream i protection level γ so as to maximize the associated reduction of distortion $RD_{i,\gamma}$ under a budget constraint B_{av} .

This problem is formalised by:

$$\text{Maximize } \sum_{i=1}^S \frac{RD_{i,y}}{l_i \cdot fec_i} \quad (4-1)$$

$$\text{Subject to } \sum_{i=1}^S l_i \cdot fec_i \leq B_{\alpha} \quad (4-2)$$

4.2 Reduction of distortion metric

D. Taubman [15] and A. Descampe and al [16], characterize a JPEG 2000 packet by its precinct indices r and p (where r and p are respectively its resolution and spatial location), and by its layer index q , s.t. $0 \leq q \leq Q$, with Q denoting the total number of quality layers. Defining $RD(r, p, q)$ to be the amount by which the distortion, measured on the whole original image, is decreased if the (r, p, q) is decoded compared to the distortion if only the packets (r, p, α) , $\alpha < q$, are decoded. A. Descampe and al come to the conclusion that the metric $RD(r, p, q)$ is additive, i.e. the gain in quality provided on the entire image by multiple packets has to be equal to the sum of the gain provided by each individual packet. So approximating the additive distortion by the Mean Square Error (MSE) defined in [17], they derive the distortion D_{α}^q associated to the reconstruction of the codeblock B_{α} from its first q quality layers:

$$D_{\alpha}^q = w_{b_{\alpha}}^2 \sum_{(x,y) \in B_{\alpha}} [\hat{c}_{\alpha}^q(x, y) - c_{\alpha}(x, y)]^2 \quad (4-3)$$

Where $c_{\alpha}(x, y)$ denotes the subband coefficient in the codeblock B_{α} , $\hat{c}_{\alpha}^q(x, y)$ denotes the quantized representation of these coefficients associated to the first q quality layers, and $w_{b_{\alpha}}$ denotes the L2-norm of the wavelet basis functions for the subband to which the codeblock B_{α} belongs. Denoting $\Gamma(r, p)$ the set of codeblocks belonging to precinct (r, p) , the incremental reduction of distortion $RD(r, p, q)$ associated to the decoding of packet (r, p, q) is given by:

$$RD(r, p, q) = \sum_{\alpha \in \Gamma(r, p)} D_{\alpha}^{(q-1)} - \sum_{\alpha \in \Gamma(r, p)} D_{\alpha}^q \quad (4-4)$$

The FEC allocation algorithm is based on this central metric $RD(r, p, q)$ derived from a codestream index file. The codestream index file is generated by the OpenJPEG library (<http://www.openjpeg.org>) and defines the gain in quality and the range of bytes corresponding to each packet. In the following we denote $RD(r, p, q)$ as RD_{pack}^i , the incremental reduction of distortion associated to decoding of packet i (packet i is characterized by the corresponding r and p).

4.3 Decoding error probability estimation

Considering an 8-bit oriented Gilbert model in [18], R. Yee and J. Weldon derive the SER (Symbol Error Rate), thanks to the formula 3-3. Defining φ to be the correlation between two consecutive error symbols X_1 and X_2 , they show that:

$$\varphi = \frac{E((X_1 - SER)(X_2 - SER))}{\sigma^2} \quad (4-5)$$

$$\varphi = p_{bb} + p_{gg} - 1$$

Solving (3-3) and (4-5), we have:

$$p_{gg} = 1 - SER(1 - \varphi)$$

$$p_{bb} = 1 - (1 - SER)(1 - \varphi)$$

Thus the transition matrix is expressed by:

$$P = \begin{bmatrix} 1 - SER(1 - \varphi) & (1 - SER)(1 - \varphi) \\ SER(1 - \varphi) & 1 - (1 - SER)(1 - \varphi) \end{bmatrix} \quad (4-6)$$

R. Yee and J. Weldon also consider the impact of interleaving data to level I . In this case they show that φ is replaced by φ^I and P along with the transmission probabilities become:

$$P = \begin{bmatrix} 1 - SER(1 - \varphi^I) & (1 - SER)(1 - \varphi^I) \\ SER(1 - \varphi^I) & 1 - (1 - SER)(1 - \varphi^I) \end{bmatrix} \quad (4-7)$$

Hence, we obtain:

$$p_{gg,I} = 1 - SER(1 - \varphi^I) \quad (4-8)$$

$$p_{bb,I} = 1 - (1 - SER)(1 - \varphi^I)$$

Relying on the double recursion method in [18], we derive $P(m, n)$, the probability of m errors in a sequence of n symbols:

$$P(m, n) = P_G(m, n) + P_B(m, n) \quad (4-9)$$

Where $P_G(m, n)$ is the probability of m errors in n transmissions with the channel ending in state G and $P_B(m, n)$ the probability of m errors in n transmissions with the channel ending in state B .

For the simplified Gilbert channel, $P_G = 0$ and $P_B = 1$ and we have:

For $n = 1, 2, 3, \dots$ and $m = 0, 1, 2, \dots, n$

$$P_G(m, n) = P_G(m, n-1)p_{gg} + P_B(m, n-1)(1 - p_{bb}) \quad (4-10)$$

$$P_B(m, n) = P_B(m-1, n-1)p_{bb} + P_G(m-1, n-1)(1 - p_{gg}) \quad (4-11)$$

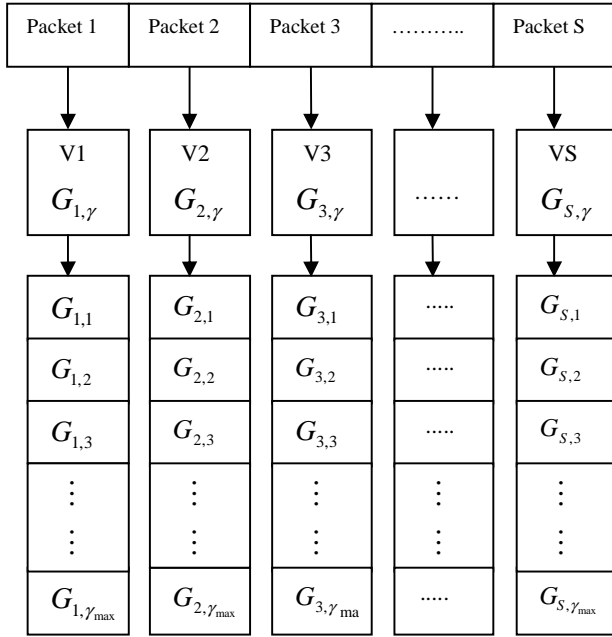


Figure 8. JPEG 2000 data packets and possible gain associated to their protection

After the merging step where all the vectors are filled with strictly decreasing gains, all the vectors (V1,V2,V3,...,VS) are collected into an overall big vector (v_{all}). Then, this vector is reorganized in decreasing order of gain. The last step is, to select the elements of the now strictly decreasing gains vector ($v_{all_ordered}$) and their corresponding protection level. For each packet, the optimal protection level is derived from the maximum related gain value selected when meeting the rate constraint (Bandwidth available B_{av}).

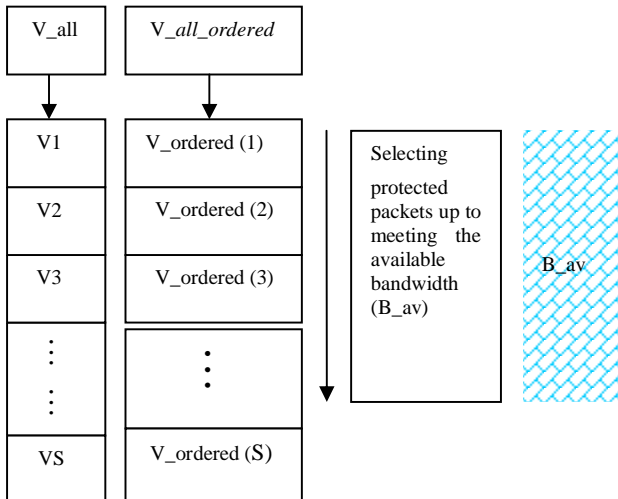


Figure 9. Gains selection by decreasing order of importance

4.5 Synopsis of the FEC rate allocation scheme and algorithm

Synopsis of the optimal FEC rate allocation algorithm:

Algorithm:

For each JPEG 2000 image

- Model the channel with a Gilbert model and for each possible protection level γ , evaluate the probability of incorrect word decoding $P_{pack}^{i,\gamma}$

- For $i=1$ to $i=S$ (Number of JPEG 2000 packets)

For $\gamma=1$ to $\gamma=\gamma_{\max}$

Estimate $RD_{i,\gamma} = (1 - P_{pack}^{i,\gamma}) \cdot RD_{pack}^i$

$$G_{i,\gamma} = \frac{RD_{i,\gamma} - RD_{i,\gamma-1}}{(fec_{\gamma} - fec_{\gamma-1}) \cdot l_i}$$

$$V(i)[\gamma] = G_{i,\gamma}$$

End For

- Merging $v_{(i)}$ vectors protection levels if necessary to ensure that $v_{(i)}$ vectors are constituted of strictly decreasing gains values

- Collecting $v_{all} = V(i)$

End For

- Ordering v_{all} on decreasing order of importance values ($v_{all_ordered}$)

- Selecting each gain value, corresponding to a specific protection level, up to meeting the rate constraint

- Optimally protect JPEG 2000 packets with the corresponding Reed-Solomon codes

End For

4.6 Proposed Scheme Complexity

In order to derive the complexity of the proposed FEC rate allocation scheme, we divide the algorithm into three parts. The first one consists in the evaluation of the gain vectors. The second part corresponds to the merging step and the last part is dedicated to ordering vector v_{all} . Let remind that the number of JPEG 2000 codestreams is s and the number of protection levels is γ_{\max} (γ_{\max} is fixed to 16 in [4]). Hence, we have:

Complexity of gains vectors estimation: $O(s \cdot \gamma_{\max})$

Complexity of merging step: $O(s \cdot \frac{(\gamma_{\max})^2}{2})$

Complexity of v_{all} ordering: $O((s \cdot \gamma_{\max})^2)$

We conclude that the overall complexity of our scheme is $O((s \cdot \gamma_{\max})^2)$. The complexity of layered based FEC rate allocation scheme such as the one proposed in [13] is low and is generally of order $O((L \cdot \gamma_{\max})^2)$ where L stands for the number of JPEG 2000 layers. Thus, we can infer that our scheme is slightly more complex as far as the ratio between the number of substreams and the number of JPEG 2000 layers is low. However, if the number of substreams is significantly higher compared to the number of layers, the proposed scheme may not be suitable for highly delay constrained video streaming applications. An interesting extension to this work could be to combine both algorithms in a smart FEC rate allocation scheme. In this smart scheme, the packet oriented unequal error protection scheme proposed in this paper could be used for JPEG 2000 frames with reasonable number of substreams ($s \leq 1000$), while layered based unequal error protection scheme will be preferred when the number of JPEG 2000 substreams significantly increases.

4.7 A practical scenario

Let consider the following scenario to illustrate how our optimal packet oriented FEC rate allocation algorithm works.

Scenario:

Available bandwidth: $B_{av} = 100$ bytes

Gilbert model parameters derived from traces analysis:
 $p_{bg} = 0.9445$ and $p_{gb} = 0.0618$

Two JPEG 2000 images codestreams packets: pack1 and pack2

Pack1 had a length $l_1 = 20$ bytes and it yields a reduction of distortion $RD_{pack}^1 = 100$

Pack2 had a length $l_2 = 40$ bytes and it yields a reduction of distortion $RD_{pack}^2 = 50$

Let assume that there are 3 possible protection levels $\gamma = 1, 2, 3$ corresponding respectively to RS(38,32), RS(40,32) and RS(45,32).

How to optimally select the FEC rate?

Applying our FEC rate allocation algorithm:

- Estimating the decoding error probability leads to:

for protection level $\gamma = 1$ we have $fec_1 = \frac{38}{32} = 1.1875$

and estimated $P_e = 0.008112$

for protection level $\gamma = 2$ we have $fec_2 = \frac{40}{32} = 1.25$

and estimated $P_e = 0.000625$

for protection level $\gamma = 3$ we have $fec_3 = \frac{45}{32} = 1.40625$

and estimated $P_e = 0.000007$

- Estimating JPEG 2000 decoding error probability $P_{pack}^{i,\gamma}$, we have:

$$P_{pack}^{1,1} = 0.008$$

$$P_{pack}^{2,1} = 0.016$$

$$P_{pack}^{1,2} = 0.001$$

$$P_{pack}^{2,2} = 0.001$$

$$P_{pack}^{1,3} = 7.10^{-6}$$

$$P_{pack}^{2,3} = 1.39 \cdot 10^{-5}$$

- Estimating reduction of distortion and gains vectors:

Reduction of distortion $RD_{i,\gamma}$:

$$RD_{1,1} = 83.52$$

$$RD_{2,1} = 8.28$$

$$RD_{1,2} = 79.95$$

$$RD_{2,2} = 7.99$$

$$RD_{1,3} = 71.11$$

$$RD_{2,3} = 7.11$$

Corresponding gains vectors estimation:

(V1)

(V2)

$$G_{1,1} = 3.5169$$

$$G_{2,1} = 0.3488$$

$$G_{1,2} = 63.96$$

$$G_{2,2} = 3.196$$

$$G_{1,3} = 22.75$$

$$G_{2,3} = 1.1376$$

Merging vectors

Step 1

(V1)

(V2)

$$\hat{G}_{1,2} = 3.19$$

$$\hat{G}_{2,2} = 0.16$$

$$G_{1,3} = 22.75$$

$$G_{2,3} = 1.14$$

Step 2

(V1)

(V2)

$$\hat{G}_{1,3} = 0.81$$

$$\hat{G}_{2,3} = 0.13$$

Building vector v_{all} :

(v_{all})

V1

0.81

V2

0.13

Ordering vector v_{all} into $v_{all_ordered}$:

($v_{all_ordered}$)

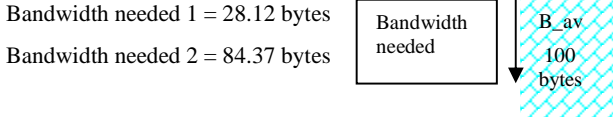
$$\hat{G}_{1,3} = 0.81$$

$$\hat{G}_{2,3} = 0.13$$

Selecting the gains values up to meeting the budget constraint:

$$\hat{G}_{1,3} = 0.81 \quad Cost_{1,3} = 28.12 \text{ bytes (bandwidth needed 1)}$$

$$\hat{G}_{2,3} = 0.13 \quad Cost_{2,3} = 56.25 \text{ bytes (bandwidth needed 2)}$$



Deriving each packet FEC rate:

$$\hat{G}_{1,3} \text{ means Pack1 should be protected with RS(45,32)}$$

$$\hat{G}_{2,3} \text{ means Pack2 should also be protected with RS(45,32)}$$

It is worth noticing that having less available bandwidth, $B_{av} = 70$ for example, would have led to selecting only $\hat{G}_{1,3}$, and so, protecting and transmitting only Pack1 with RS(45,32).

5. JPEG 2000 IMAGE AND VIDEO STREAMING OVER REAL MANET TRACES WITH OPTIMAL FEC RATE ALLOCATION

The goal of this section is to show the results achieved while streaming JPEG 2000 based images/video over real MANET traces and to highlight the practical interest of the proposed JPWL based system associated to our optimal FEC rate allocation algorithm.

The considered wireless channel traces are analysed in section 3 and the video sequence used is *speedway.mj2* [19] containing 200 JPEG 2000 frames generated with an overall compression ratio of 20 for the base layer, 10 for the second layer and 5 for the third layer. When dealing with a single image transmission, the corresponding image is *speedway_0.j2k* (576x720, 3 layers) which is the first image extracted from *speedway.mj2*. This image is constituted of 16 data packets.

As error occurrence in the transmission channel is a random process, different runs are made for each trials and the Mean Square Error (MSE) between the original image (I_o) and the decoded image (I_d), is averaged over all the runs in order to have statistically representative metrics.

The measured Peak Signal to Noise Ratio (PSNR) is obtained as follows:

$$MSE(I_o, I_d) = \frac{1}{M \cdot N} \sum_{x=1}^M \sum_{y=1}^N |I_o(x, y) - I_d(x, y)|^2$$

$$\overline{MSE} = \frac{MSE}{N_{frames}}$$

$$PSNR = 10 * \log_{10} \left(\frac{255^2}{\overline{MSE}} \right)$$

Where \overline{MSE} is the Mean Square Error over all the N_{frames} considered images. In the case of Motion JPEG 2000 streaming, N_{frames} represents the 200 JPEG 2000 frames constituting the video sequence and in the single image transmission case, N_{frames} represents the number of trials needed to have a statistically representative metric. Each PSNR measure is associated to a successful decoding rate metric which corresponds to decoder crash avoidance on the basis of 1000 transmission trials.

5.1 On JPEG 2000 codestreams interleaving

In this section, we evaluate the impact of data interleaving in the effectiveness of the FEC rate allocation scheme. Thanks to the interleaving matrix presented in Figure 10, protected JPEG 2000 data are decorrelated before being sent through the wireless channel. Hence, the impact of consecutive channel errors sequences on the transmitted codestreams is reduced. In Figure 10 the protected JPEG 2000 codestream is divided into P_x packets of length N . Then, the interleaving process consists in storing M consecutive packets into a $M \times N$ matrix and to read the columns of this matrix so that two initially consecutive symbols are separated by a distance of $I = M$ (symbols). We refer to I as the interleaving degree.

The considered channel is a real mobile ad-hoc network channel experiencing $PER = 3.88 * 10^{-2}$ and the interleaving degrees are 1, 2, 4, 8, 16, 32, 64 and 128. Table 1 shows the PSNR evolution as function of interleaving degree I . The considered image is *speedway_0.j2k* protected with our optimal JPWL compliant scheme.

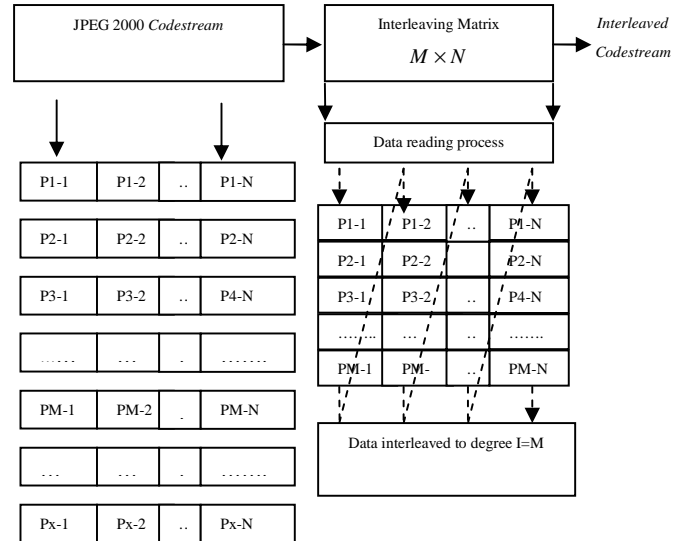


Figure 10. Interleaving process

The interest of interleaving is shown in table 1 in the sense that the PSNR and the successful decoding rate increase with the interleaving degree I .

Table 1. Interleaving degree and associated image PSNR

Interleaving degree I	PSNR (dB)	Successful Decoding Rate
$I=1$	24.1	77.5
$I=2$	24.6	89.8
$I=4$	25.2	92.1
$I=8$	31.8	93.4
$I=16$	38.7	94.5
$I=32$	44.33	94.7
$I=64$	44.38	94.9
$I=128$	44.37	94.8

The results in table 1 are valid for a Gilbert channel with a specific error correlation factor and are no longer the same when this factor changes. For the considered channel, we observe that for $I \leq 8$, interleaving has no noticeable impact because the interleaving degree I is smaller than the average error burst length. In fact, we show in section 3.2.2 that the upper bound of the mean error burst length is $L_b^{\max} = 10$ bytes. Hence, in order to be efficient, the interleaving degree should be higher than 10 bytes. Hence, when I is increased to 16 or more, we notice an improvement of both the PSNR and the successful decoding rate. However, we observe that higher values of I (128) yield only slight improvement in terms of PSNR while consuming considerable memory resources leading to the conclusion that reasonable interleaving degree (typically $I = 16$ or $I = 32$) is a good compromise.

5.2 JPEG 2000 image/video streaming over real MANET channel traces

5.2.1 Optimal FEC rate allocation

Figure 11 presents incremental reduction of distortion (RD_i^0) associated to decoding of the 16 packets of *speedway_0.j2k* image. We observe that packet 0 to 5 have the most important reduction of distortion values and thus are the most important packets. Hence they should be protected by Reed-Solomon codes with higher error correcting ability than other packets.

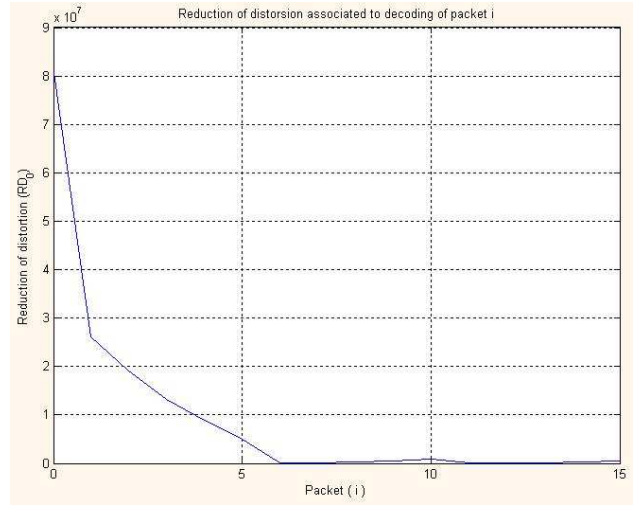


Figure 11. Reduction of Distortion of JPEG 2000 packets

Figure 12 shows the $RS(n,k)$ codes error correcting ability $t = \frac{n-k}{2}$ applied for the protection of the 16 packets of *speedway_0.j2k*. The considered system experiences a Carrier to noise Ratio $\frac{C}{N} = 17dB$ corresponding to $PER = 2.4 * 10^{-2}$. In this

figure, we compare the results achieved when applying the dynamic FEC allocation rate heuristic proposed in [14], the layered Unequal protection presented in [13], the Equal Error Protection (EEP with $RS(40,32)$, protection rate 4/5) and our optimal FEC rate allocation scheme. The available bandwidth in the system is 6 Mbit/s.

We observe that the EEP scheme applies the same protection rate to all JPEG 2000 packets whereas the optimal FEC rate scheme allocates more powerful codes from packet 0 to packet 5 (first layer) and protects the other packets at lower level which is coherent when considering the importance of each packet. Moreover, packet 6 to 15 (second layer and third layer) which yield low reduction of distortion are less protected because they are less important.

The dynamic FEC rate allocation highly protects the first important packets (layer 1 and layer 2) but does not protect the last layer due to restricted bandwidth budget. The layered UEP proposed by Z. Guo, applies less powerful RS codes so that all the layers are protected. Contrarily to the proposed optimal scheme, both layered oriented schemes protect all the packets of the same layer at the same rate but they do not manage to take the difference between packets into account. In other words, in case of fast varying channel, the layered oriented protection scheme may not be sufficiently efficient to guarantee QoS to wireless clients.

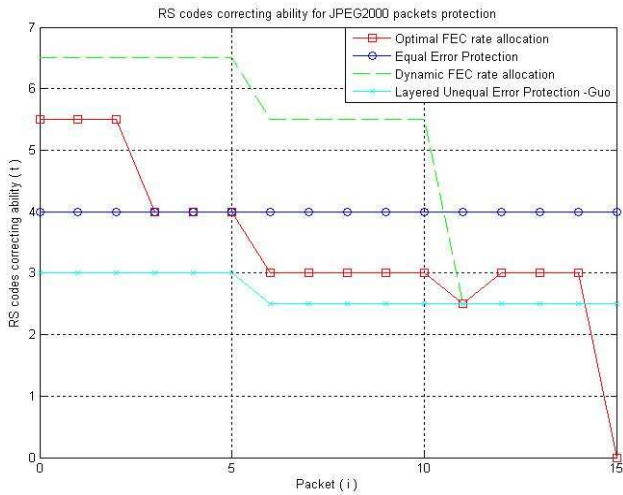


Figure 12. Correcting ability of the $RS(n,32)$ codes used for JPEG 2000 data packets – Bandwidth of 6 Mbit/s

5.2.2 Performance of the optimal FEC rate allocation methodology: application to wireless Motion JPEG 2000 video transmission over real MANET channel traces

In this section, performance of the optimal FEC rate allocation methodology is evaluated using speedway.mj2 [19] video streaming over real MANET channel traces [7]. The available bandwidth in the system is 6 Mbit/s.

In Figure 13, we present the successful decoding rate of the transmitted video for different Carrier to Noise Ratio. For $\frac{C}{N} \leq 14dB$, we observe that the optimal FEC rate allocation performs from 2% to 10% better than layered UEP and EEP in terms of successful decoding rate. For the dynamic FEC rate allocation methodology, for $\frac{C}{N} = 11dB$, we notice that the successful decoding rate is about 50%. It means that we lost half transmitted frames, which is intolerable for video streaming applications. Hence, for highly noised channel, typically $\frac{C}{N} \leq 14dB$,

the proposed optimal scheme yields a sensitive improvement of the successful decoding rate when compared to layered UEP, dynamic scheme and EEP.

However for noisy and slightly noisy channels where the Carrier to Noise Ratio is respectively between $14dB < \frac{C}{N} \leq 18dB$ and

$\frac{C}{N} \geq 18dB$, the performances of all the presented methodologies in terms of successful decoding rate are close. This is because less protection is required to correct transmission errors, so even inefficient selection of RS codes could help avoiding decoder crashes.

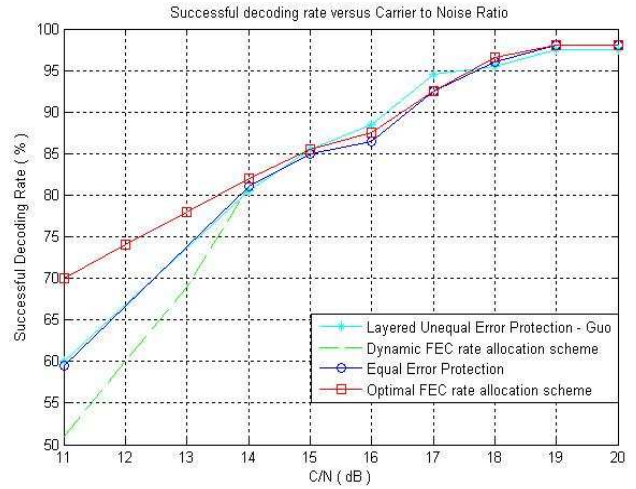


Figure 13. Successful decoding rate

Figure 14 presents the PSNR of decoded video at user equipment for different channel conditions (Carrier to Noise ratio ranging from 11 to 20 dB).

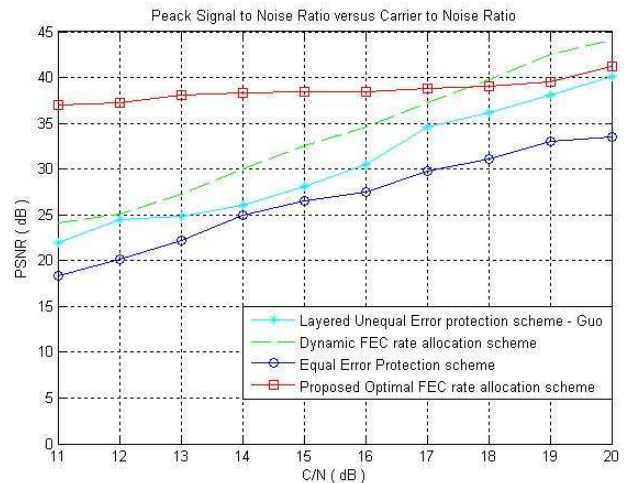


Figure 14. PSNR versus Carrier to Noise Ratio

We notice that the proposed optimal FEC rate allocation mechanism allows robust JPEG 2000 codestream streaming over mobile ad-hoc networks. In fact, in terms of PSNR it performs significantly better than existing FEC rate allocation schemes thanks to efficient selection of RS codes. Hence, for highly noised channel, typically $\frac{C}{N} \leq 14dB$ which corresponds to $PER \leq 9.9 \cdot 10^{-2}$,

the dynamic FEC rate allocation presented in [14] outperforms the layered UEP scheme proposed by Z. Guo and al in [13]. However, for both schemes the Peak Signal to Noise Ratio is still below 30dB, leading to unpleasant video quality. Both layered oriented methodologies are less effective than the optimal scheme, because the last one manages to take into account the importance of each packet constituting a JPEG 2000 frame. Hence, while both methodologies apply a selected RS code for a layer, the optimal schemes applies different selected RS codes for JPEG 2000 packets leading to more accurate protection level selection.

We also notice that EEP is not effective for wireless channel subjected to high level of transmission errors because of bad performance in terms of PSNR ($PSNR \leq 25dB$).

For noisy channel, typically $14dB < \frac{C}{N} \leq 18dB$ the proposed optimal

FEC rate allocation scheme performs from 4dB to 11dB more than layered UEP and from 9dB to 13dB more than EEP scheme. It is interesting to notice that the effectiveness of dynamic FEC rate allocation scheme is increased up to meeting the optimal point. This is due to the fact that FEC rate is dynamically adapted to transmission condition which leads to better selection of RS codes. For slightly noisy channel, typically $18dB < \frac{C}{N} \leq 20dB$, our

proposed scheme outperforms both EEP and layered UEP scheme and the dynamic FEC rate allocation scheme is the only one to achieve similar performance.

The main advantage of the proposed optimal FEC is its high ability to adapt channel coding to transmission environment. Hence, thanks to an efficient selection of RS codes, our optimal scheme maintains the video quality at a high and stable quality level (between 35dB and 42 dB). Contrary to the scheme proposed in this paper, the dynamic FEC rate allocation, the layered UEP scheme and other suboptimal schemes such as EEP, yield significant variation of the streamed video quality resulting in disgraceful visualisation at user equipment. Hence, the optimal rate allocation proposed in this paper allows guaranteeing Quality of Service to wireless client.

6. CONCLUSION

In this paper, a JPWL compliant system based on an optimal FEC rate allocation scheme for robust transmission of JPEG 2000 images and video over MANET is presented.

The paper starts by an overview of JPEG 2000 and Wireless JPEG 2000 (JPWL - Part 11 of JPEG 2000 standards) and then the proposed system functionalities are presented.

We analyze real mobile ad-hoc network traces. Then we discuss the problem of FEC rate allocation and propose an optimal JPWL compliant methodology for FEC rate allocation.

Interesting results are then presented to illustrate the effectiveness of the proposed scheme. The impact of data interleaving is also investigated. We then demonstrate that the proposed optimal FEC allocation methodology outperforms existing layered oriented Unequal Error Protection schemes, using an application of Motion JPEG 2000 video streaming over real MANET channel traces.

Summarizing we can say that JPEG 2000, including the JPWL features, is a good point of departure to achieve robust video transmissions over noisy channels. Hence, we consider the proposed JPWL compliant system based on our optimal FEC rate allocation scheme, as a valid step toward guaranteeing Quality of Service in JPEG 2000 based wireless multimedia systems.

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