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Research Article

Optimal JPWL Forward Error Correction Rate Allocation for Robust JPEG 2000 Images and Video Streaming over Mobile Ad Hoc Networks

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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.

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 on the transmission environment.

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

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 resynchronize 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 (FEC), 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, 3]. However, as packets errors mainly occur in bursts, the channel model considered in these 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

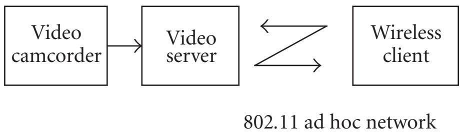


Figure 1: Wireless video streaming system.

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 modeling 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.

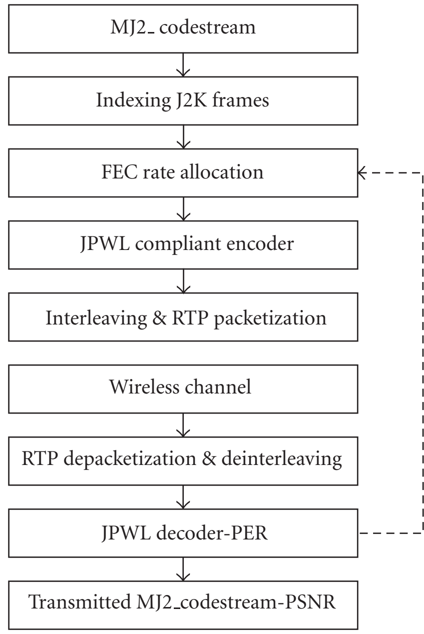


Figure 2: JPWL-based system functionalities.

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.

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 Uplink.

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 noting that Futemma et 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

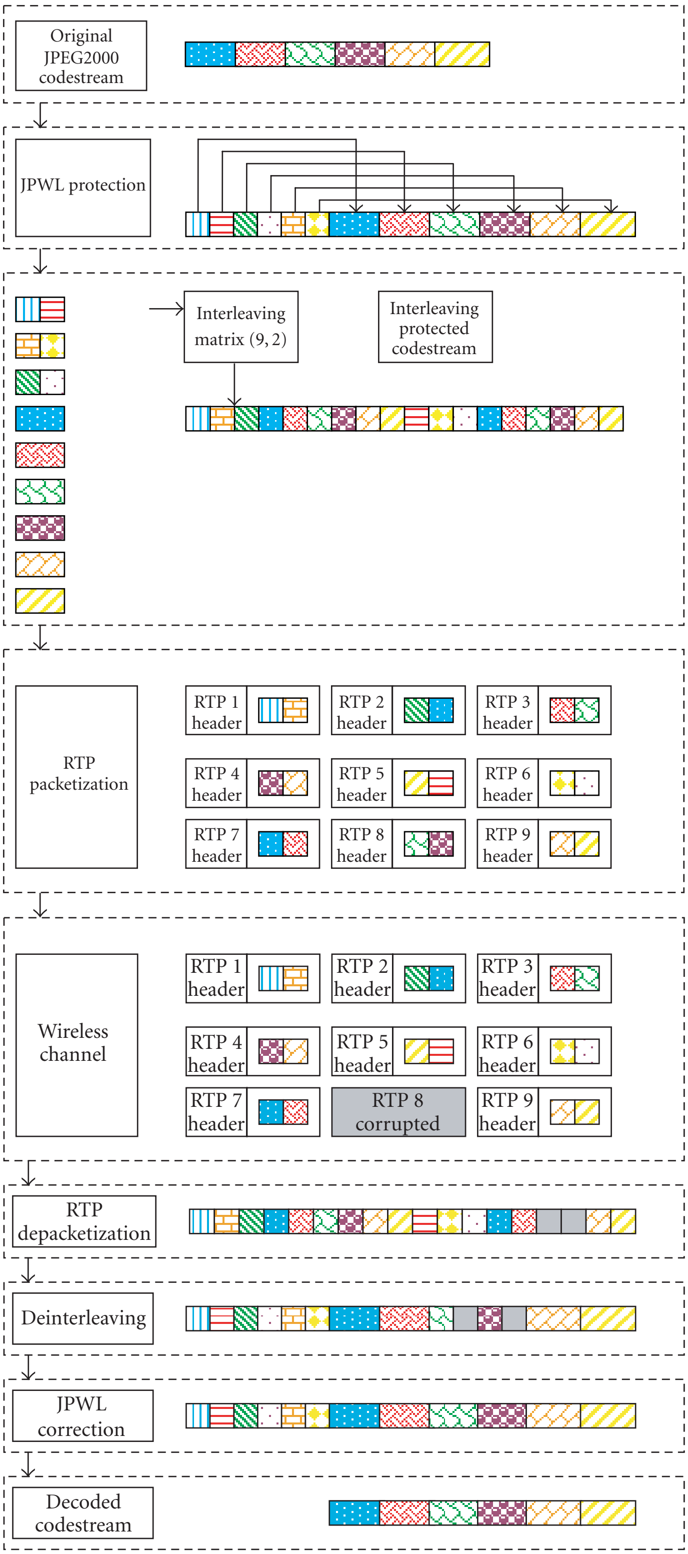


Figure 3: JPEG 2000 codestreams transmission through the proposed JPWL system.

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 de-interleaved. 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 improves the design of the FEC rate allocation mechanism, we dedicate the following section to the analysis and modeling of real MANET channel traces.

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 errors 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 occurs with other stations.

The set of generated loss patterns covers different transmission scenarios (mobile or static). Each pattern corresponds to a specific carrier-to-noise ratio C/N (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 18 Mbps. In the considered loss patterns, C/N varies between 20 dB and 11 dB, which corresponds to a packet error rate ranging from 5.1×10^{-3} to 2.662×10^{-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 modeled 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 modeled as a two-state Markov process (Figure 5).

WLI-CB-G54A buffalo 802.11 (b/g) (a) F5D7010 belkin 54G IEEE 802.11 (b/g) (b)

Figure 4: Loss patterns generation platform.

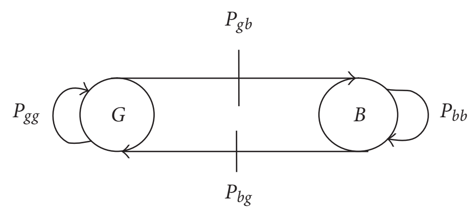


Figure 5: Two-state Markov process scheme.

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.

In Markov chains with finite state space, the transition probability distribution can be represented by a matrix called transition matrix P. The $(i, j)^{\text{ième}}$ 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

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

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

$$\pi_G = \frac{1 - p_{bb}}{1 - p_{bb} + 1 - p_{gg}}, \qquad \pi_B = \frac{1 - p_{gg}}{1 - p_{bb} + 1 - p_{gg}}. \quad (2)$$

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

$$L_G = \frac{1}{1 - p_{gg}}, \qquad L_B = \frac{1}{1 - p_{bb}}. \quad (3)$$

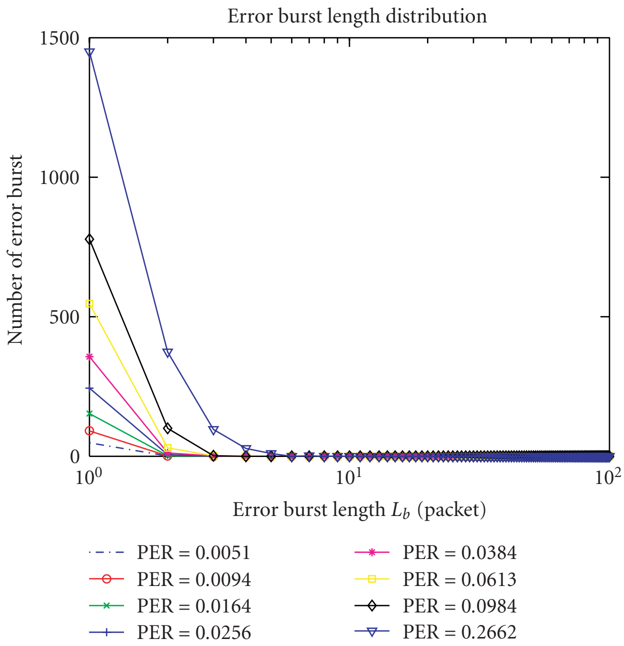


FIGURE 6: Error bursts distribution.

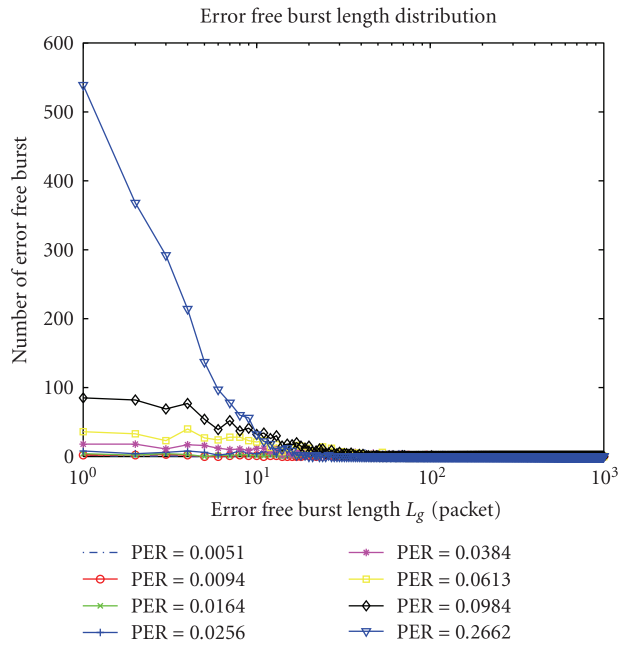


FIGURE 7: Error-free burst length distribution.

Applying Markov process at symbol level, the symbol error rate (SER) for GE is

$$\text{SER} = P_G\pi_G + P_B\pi_B = \frac{P_G(1-p_{bb}) + P_B(1-p_{gg})}{(1-p_{bb}+1-p_{gg})}. \quad (4)$$

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

$$\text{SER} = \frac{1-p_{gg}}{1-p_{bb}+1-p_{gg}}. \quad (5)$$

A comprehensive description of Markov-based wireless channel modeling 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.

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 times 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.

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 Jain [11]:

$$p_{gb} = \frac{1}{L_G}, \qquad p_{bg} = \frac{1}{L_B}. \quad (6)$$

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 Thomos et al. [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, Guo et 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 layer-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 Section 4.1 we formalize the FEC rate allocation problem and introduce in Section 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. Section 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 of 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 $0 \le \gamma \le \gamma_{\max}$, 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} be the byte budget constraint corresponding to the available bandwidth in the system.

Let l_i be the length in bytes of the ith 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 $R = k/n$. We define fec $= 1/R = n/k$ as the invert of the channel coding rate, so $l_i \times \text{fec}$ represents, in byte, the increase of the ith 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 the reduction of distortion associated to decoding of packet i, and $\text{RD}_{i,\gamma}$ the reduction of distortion achieved when packet i is protected at level γ ($\text{RD}_{i,\gamma}$ will be further formalized). We define the gain as the ratio between the image quality improvement $\text{RD}_{i,\gamma}$ and the associated cost in terms of bandwidth consumption $l_i \times \text{fec}$.

Thus, the FEC rate allocation problem can be stated as: how to optimally select substream i protection level γ in order to maximize the associated reduction of distortion $\text{RD}_{i,\gamma}$ under a budget constraint B_{av}.

This problem is formalized by the following:

$$\begin{aligned} &\text{maximize} \sum_{i=1}^{S} \frac{\text{RD}_{i,\gamma}}{l_i \cdot \text{fec}_i}, \\ &\text{subject to} \sum_{i=1}^{S} l_i \cdot \text{fec}_i \le B_{\text{av}}. \end{aligned} \tag{7}$$

4.2. Reduction of distortion metric

Taubman and Rosenbaum [15] and Descampe et al. [16] characterize a JPEG 2000 packet by its precinct indices r and p (where r and p are, resp., its resolution and spatial location), and by its layer index q, s.t $0 \le q \le Q$, with Q denoting the total number of quality layers. Defining $\text{RD}(r,p,q)$ to be the amount by which the distortion, measured on the whole original image, is decreased if packet (r,p,q) is decoded compared to the distortion if only the packets (r,p,α), $\alpha < q$, are decoded. Descampe et al. come to the conclusion that the metric $\text{RD}(r,p,q)$ is additive, meaning that 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:

$$D_\alpha^q = w_{b_\alpha}^2 \sum_{(x,y)\in B_\alpha} \left[\hat{c}_\alpha^q(x,y) - c_\alpha(x,y)\right]^2, \tag{8}$$

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_α} 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 $\text{RD}(r,p,q)$ associated to the decoding of packet (r,p,q) is given by

$$\text{RD}(r,p,q) = \sum_{\alpha\in\Gamma(r,p)} D_\alpha^{(q-1)} - \sum_{\alpha\in\Gamma(r,p)} D_\alpha^q. \tag{9}$$

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 Open JPEG 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 $\mathrm{RD}^i_{\mathrm{pack}}$, 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], Yee and Weldon derive the symbol error rate (SER), thanks to the formula (5). Defining φ to be the correlation between two consecutive error symbols X_1 and X_2, they show that

$$\begin{aligned} \varphi &= \frac{E\big((X_1 - \mathrm{SER})(X_2 - \mathrm{SER})\big)}{\sigma^2}, \\ \varphi &= p_{bb} + p_{gg} - 1. \end{aligned} \tag{10}$$

Solving (5) and (10), we have

$$\begin{aligned} p_{gg} &= 1 - \mathrm{SER}(1-\varphi), \\ p_{bb} &= 1 - (1-\mathrm{SER})(1-\varphi). \end{aligned} \tag{11}$$

Thus the transition matrix is expressed by

$$P = \begin{bmatrix} 1 - \mathrm{SER}(1-\varphi) & (1-\mathrm{SER})(1-\varphi) \\ \mathrm{SER}(1-\varphi) & 1-(1-\mathrm{SER})(1-\varphi) \end{bmatrix}. \tag{12}$$

Yee and 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

$$P = \begin{bmatrix} 1 - \mathrm{SER}(1-\varphi^I) & (1-\mathrm{SER})(1-\varphi^I) \\ \mathrm{SER}(1-\varphi^I) & 1-(1-\mathrm{SER})(1-\varphi^I) \end{bmatrix}. \tag{13}$$

Hence, we obtain the following:

$$\begin{aligned} p_{gg,I} &= 1 - \mathrm{SER}(1-\varphi^I), \\ p_{bb,I} &= 1 - (1-\mathrm{SER})(1-\varphi^I). \end{aligned} \tag{14}$$

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

$$P(m,n) = P_G(m,n) + P_B(m,n), \tag{15}$$

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 the following.

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

$$\begin{aligned} P_G(m,n) &= P_G(m,n-1)p_{gg} + P_B(m,n-1)(1-p_{bb}), \\ P_B(m,n) &= P_B(m-1,n-1)p_{bb} + P_G(m-1,n-1)(1-p_{gg}). \end{aligned} \tag{16}$$

The initials conditions of the double recursion are

$$\begin{aligned} P_B(0,0) &= \frac{1-p_{gg}}{1-p_{bb}+1-p_{gg}}, \\ P_G(0,0) &= \frac{1-p_{bb}}{1-p_{bb}+1-p_{gg}} \end{aligned} \tag{17}$$

with $P_B(m, 0) = P_G(m, 0) = 0$ for $m \neq 0$.

From these developments we derive P_e the decoding error probability of an n-symbol sequence protected with a channel code of capacity t:

$$P_e = \sum_{m=t+1}^{n} P(m,n). \tag{18}$$

In our system, the channel code is a Reed-Solomon code defined by RS(n, k) and its corresponding capacity is $t = (n-k)/2$. Hence, the information word is a k-symbol packet.

It is worth noting that the JPWL final draft [4] defines 16 Reed-Solomon codes for JPEG 2000 data protection. All those recommended RS(n,k) codes have a fixed k = 32 bytes. Considering each JPEG 2000 packets as an η_w-information word packet and denoting P_e as the probability that a decoded word is incorrect, we derive the JPEG 2000 packet decoding error probability P_{pack}.

$$\eta_w(\text{number of word}) = \frac{\text{packet length (bytes)}}{k(=32\,\text{bytes})}, \tag{19}$$

$$\begin{aligned} P_{\mathrm{pack}} = {} & (\text{Probability that 1 word is incorrect} \\ & \quad \text{and } (\eta_w - 1) \text{ words are well decoded}) \\ & + (\text{Probability that 2 words are incorrect} \\ & \quad \text{and } (\eta_w - 2) \text{ words are well decoded}) + \cdots \\ & + (\text{Probability that all } (\eta_w) \text{ words are incorrect}) \\ P_{\mathrm{pack}} = {} & C^1_{\eta_w}(1-P_e)^{\eta_w-1}(P_e)^1 + C^2_{\eta_w}(1-P_e)^{\eta_w-2}(P_e)^2 + \cdots \\ & + C^{\eta_w}_{\eta_w}(1-P_e)^{\eta_w-\eta_w}(P_e)^{\eta_w}. \end{aligned} \tag{20}$$

Hence, we have $P_{\mathrm{pack}} = \sum_{i=1}^{n_w} C^i_{n_w}(1-P_e)^{n_w-i}(P_e)^i$.

Evaluating P_{pack} for each transmitted substream i and for different protection levels γ leads to deriving a set of possible decoding error probabilities $P^{i,\gamma}_{\mathrm{pack}}$. Each of these $P^{i,\gamma}_{\mathrm{pack}}$ metrics is of central importance when designing the optimization scheme in the following section.

4.4. Optimization

Since the optimization problem can be solved by finding the optimal protection for each substream of JPEG 2000 codestreams under a budget constraint, we define $G_{i,\gamma}$ as the gain in quality of the transmitted image obtained at the receiver side when packet i is decoded.

Let $\mathrm{RD}_{i,1}$ and $\mathrm{RD}_{i,\gamma}$ be the reduction of distortion obtained when packet i is transmitted respectively with protection level 1 and with protection level γ, we have

$$\mathrm{RD}_{i,1} = (1 - P^{i,1}_{\text{pack}})\cdot \mathrm{RD}^{i}_{\text{pack}},$$
$$\mathrm{RD}_{i,\gamma} = (1 - P^{i,\gamma}_{\text{pack}})\cdot \mathrm{RD}^{i}_{\text{pack}}. \quad (21)$$

The resulting gain is

$$G_{i,1} = \frac{\mathrm{RD}_{i,1}}{l_i} = \frac{(1 - P^{i,1}_{\text{pack}})\cdot \mathrm{RD}^{i}_{\text{pack}}}{l_i}. \quad (22)$$

Similarly, any transmission between two consecutive protection levels (γ and $\gamma + 1$) yields an improvement in terms of reduction of distortion but has a budget cost equal to $(\mathrm{fec}_{\gamma+1} - \mathrm{fec}_{\gamma}) \times l_i$, hence we have

$$G_{i,\gamma} = \frac{\mathrm{RD}_{i,\gamma} - \mathrm{RD}_{i,\gamma-1}}{(\mathrm{fec}_{\gamma} - \mathrm{fec}_{\gamma-1})\cdot l_i},$$
$$G_{i,\gamma} = \frac{(P^{i,\gamma-1}_{\text{pack}} - P^{i,\gamma}_{\text{pack}})\cdot \mathrm{RD}^{i}_{\text{pack}}}{(\mathrm{fec}_{\gamma} - \mathrm{fec}_{\gamma-1})\cdot l_i}. \quad (23)$$

Protection levels incremental gains $G_{1,1}$ to $G_{S,\gamma}$ are derived for each packet and stored in S different vectors $(V1, V2, \ldots, VS)$ as presented in Figure 8. For each vector, the gains are expected to be decreasing so that the rate-distortion curve corresponding to a specific substream is always convex and that the FEC allocation is always optimal. For example, raising substream i's protection level γ to $\gamma + 1$ yields more gain than going from level $\gamma - 1$ to γ, we have to merge the two elements in an average gain value $\widehat{G}$ given by:

$$\widehat{G} = \frac{\mathrm{RD}_{i,\gamma+1} - \mathrm{RD}_{i,\gamma-1}}{(\mathrm{fec}_{\gamma+1} - \mathrm{fec}_{\gamma-1})\cdot l_i},$$
$$\widehat{G} = \frac{(P^{i,\gamma-1}_{\text{pack}} - P^{i,\gamma+1}_{\text{pack}})\cdot \mathrm{RD}^{i}_{\text{pack}}}{(\mathrm{fec}_{\gamma+1} - \mathrm{fec}_{\gamma-1})\cdot l_i}. \quad (24)$$

After the merging step where all the vectors are filled with strictly decreasing gains, all the vectors $(V1, V2, V3, \ldots, VS)$ 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).

4.5. Synopsis of the FEC rate allocation scheme and algorithm

Synopsis of the optimal FEC rate allocation algorithm (see Algorithm 1).

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.

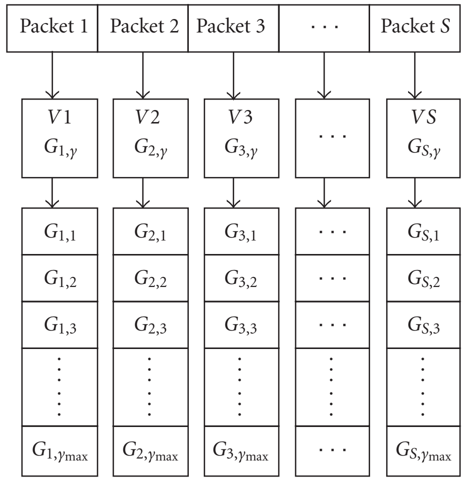


Figure 8: JPEG 2000 data packets and possible gain associated to their protection.

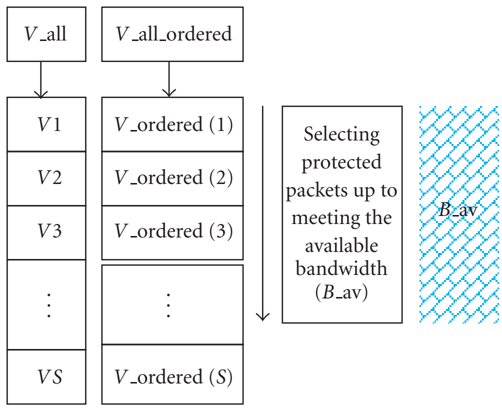


Figure 9: Gains selection by decreasing order of importance.

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 $\gamma_{\max}$ ($\gamma_{\max}$ is fixed to 16 in [4]). Hence, we have

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

complexity of merging step: $O(s\cdot((\gamma_{\max})^2/2))$;

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 layer-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

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 $P_{\text{pack}}^{i,\gamma}$
- For $i = 1$ to $i = S$ (Number of JPEG 2000 packets)
  - For $\gamma = 1$ to $\gamma = \gamma_{\max}$
    - Estimate $\text{RD}_{i,\gamma} = (1 - P_{\text{pack}}^{i,\gamma}) \cdot \text{RD}_{\text{pack}}^{i}$
    - $G_{i,\gamma} = \dfrac{\text{RD}_{i,\gamma} - \text{RD}_{i,\gamma-1}}{(\text{fec}_{\gamma} - \text{fec}_{\gamma-1}) \cdot l_i}$
    - $V(i)[\gamma] = G_{i,\gamma}$
  - End For
  - Merging $V(i)$ vectors protection levels if necessary to ensure that $V(i)$ vectors are constituted of strictly decreasing gains values
  - Collecting $V\_\text{all} = V(i)$
- End For
- Ordering V_all on decreasing order of importance values ($V\_\text{all\_ordered}$)
- 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

Algorithm 1

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 layer-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: $B\_\text{av} = 100$ bytes.

Gilbert model parameters derived from traces analysis:

$$p_{bg} = 0.9445, \qquad p_{gb} = 0.0618. \tag{25}$$

Two JPEG 2000 images codestreams packets: pack1 and pack2.

Pack1 had a length $l_1 = 20$ bytes and it yields a reduction of distortion $\text{RD}_{\text{pack}}^{1} = 100$.

Pack2 had a length $l_2 = 40$ bytes and it yields a reduction of distortion $\text{RD}_{\text{pack}}^{2} = 50$.

- Estimating the decoding error probability leads to:
  - for protection level $\gamma = 1$ we have $\text{fec}_1 = 38/32 = 1.1875$ and estimated $P_e = 0.008112$
  - for protection level $\gamma = 2$ we have $\text{fec}_2 = 40/32 = 1.25$ and estimated $P_e = 0.000625$
  - for protection level $\gamma = 3$ we have $\text{fec}_3 = 45/32 = 1.40625$ and estimated $P_e = 0.000007$
- Estimating JPEG 2000 decoding error probability $P_{\text{pack}}^{i,\gamma}$, we have

$P_{\text{pack}}^{1,1} = 0.008$ $\quad P_{\text{pack}}^{2,1} = 0.016$

$P_{\text{pack}}^{1,2} = 0.001$ $\quad P_{\text{pack}}^{2,2} = 0.001$

$P_{\text{pack}}^{1,3} = 7.10^{-6}$ $\quad P_{\text{pack}}^{2,3} = 1.39 \cdot 10^{-5}$

- Estimating reduction of distortion and gains vectors:

Reduction of distortion $\text{RD}_{i,\gamma}$:

$\text{RD}_{1,1} = 83.52$ $\quad \text{RD}_{2,1} = 8.28$

$\text{RD}_{1,2} = 79.95$ $\quad \text{RD}_{2,2} = 7.99$

$\text{RD}_{1,3} = 71.11$ $\quad \text{RD}_{2,3} = 7.11$

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 $V\_\text{all\_ordered}$:

$(V\_\text{all\_ordered})$

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

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

Algorithm 2

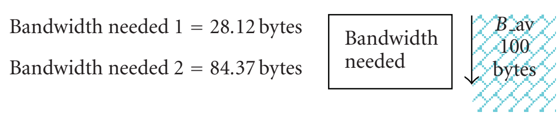
Let assume that there are 3 possible protection levels $\gamma = 1, 2, 3$ corresponding, respectively, to RS(38,32), RS(40,32), and RS(45,32).

How to optimally select the FEC rate?

We apply our FEC rate allocation algorithm (see Algorithm 2).

Selecting the gains values up to meeting the budget constraint:

$$\begin{aligned} &\hat{G}_{1,3} = 0.81 \qquad \text{Cost}_{1,3} = 28.12 \text{ bytes (bandwidth needed 1)} \\ &\hat{G}_{2,3} = 0.13 \qquad \text{Cost}_{2,3} = 56.25 \text{ bytes (bandwidth needed 2)} \end{aligned} \tag{26}$$



Deriving each packet FEC rate:

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

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

It is worth noting 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* (352 × 288, 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 trial and the mean square error (MSE) between the original image (I_o) and the decoded image (I_d) is averaged over all runs in order to have statistically representative metrics.

The measured peak signal-to-noise ratio (PSNR) is obtained as follows:

$$\begin{aligned} \mathrm{MSE}(I_o, I_d) &= \frac{1}{M \cdot N} \sum_{x=1}^{M} \sum_{y=1}^{N} \left| I_o(x,y) - I_d(x,y) \right|^2, \\ \overline{\mathrm{MSE}} &= \frac{\mathrm{MSE}}{N_{\mathrm{frames}}}, \qquad (27) \\ \mathrm{PSNR} &= 10 \times \log_{10}\left(\frac{255^2}{\overline{\mathrm{MSE}}}\right), \end{aligned}$$

where $\overline{\mathrm{MSE}}$ 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 Px packets of length N. Then, the interleaving process consists in storing M consecutive packets into an $M \times N$ 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.

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 considered channel is a real mobile ad hoc network channel experiencing PER $= 3.88 \times 10^{-2}$ 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.

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.

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 packets from 0 to 5 have the most important reduction of distortion values, therefore they are the most important packets. Hence they should be protected

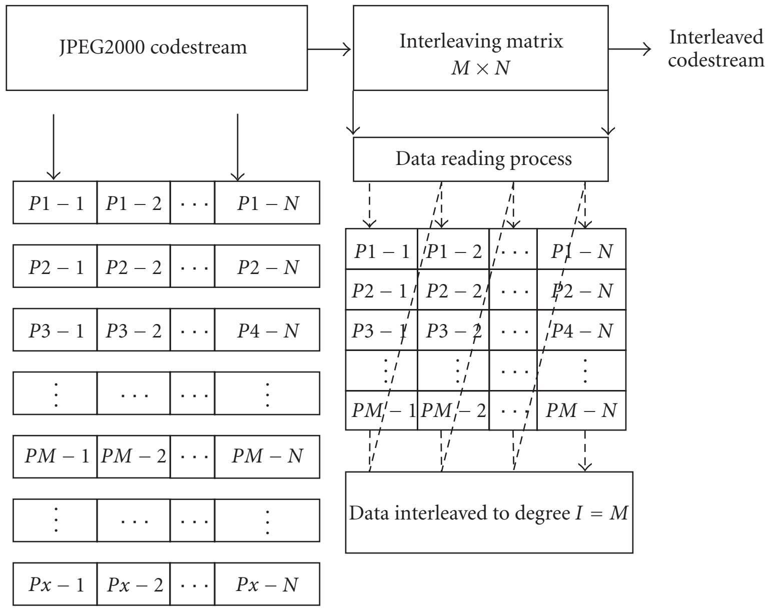


Figure 10: Interleaving process.

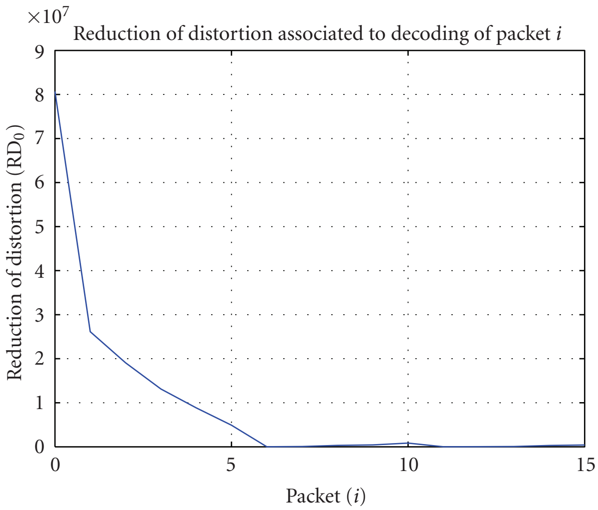


Figure 11: Reduction of distortion of JPEG 2000 packets.

by Reed-Solomon codes with higher error correcting ability than other packets.

Figure 12 shows the RS(n, k) codes error correcting ability $t = (n-k)/2$ applied for the protection of the 16 packets of *speedway_0.j2k*. The considered system experiences a carrier-to-noise ratio $C/N = 17$ dB corresponding to PER $= 2.4 \times 10^{-2}$. In this figure, we compare the results achieved when applying the dynamic FEC allocation rate heuristic proposed in [14], the layered unequal error 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 Mbps.

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, from packets 6 to 15 (second layer and third layer) which yield low reduction of distortion, therefore they 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 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.

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 Mbps.

In Figure 13, we present the successful decoding rate of the transmitted video for different carrier-to-noise ratio. For $C/N \leq 14$ dB, 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 $C/N = 11$ dB, we notice that the successful decoding rate is about 50%. It means that we lost half of the transmitted frames,

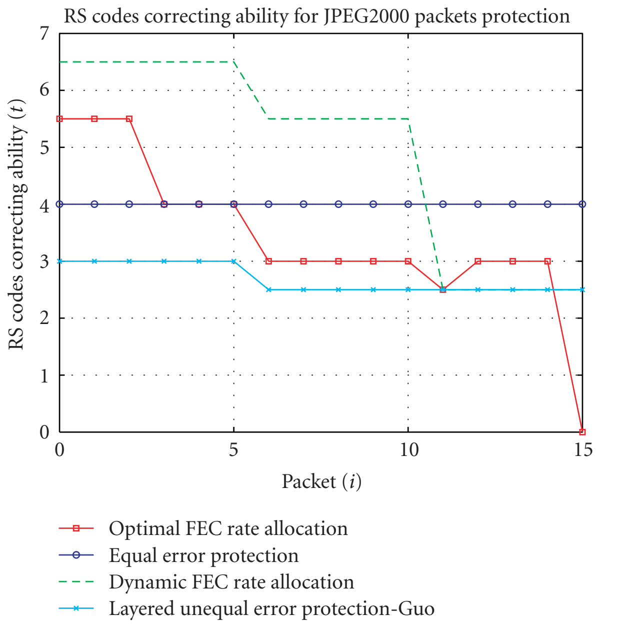


FIGURE 12: Correcting ability of the RS(n,32) codes used for JPEG 2000 data packets—bandwidth of 6 Mbps.

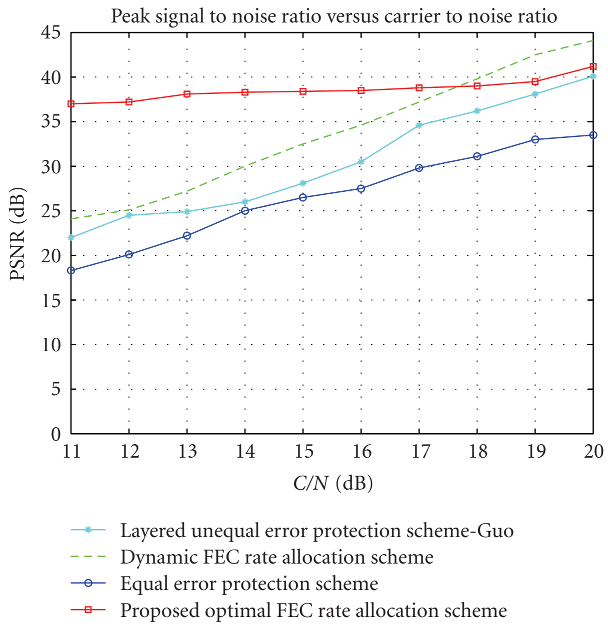


FIGURE 14: PSNR versus carrier-to-noise ratio.

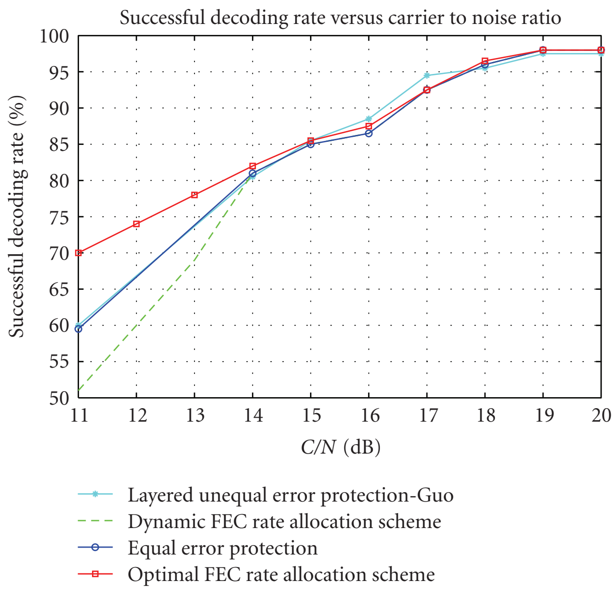


FIGURE 13: Successful decoding rate.

which is intolerable for video streaming applications. Hence, for highly noised channel, typically $C/N \leq 14$ dB, 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 $14\,\text{dB} < C/N \leq 18$ dB and $C/N \geq 18$ dB; 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 suboptimal selection of RS codes could help avoiding decoder crashes.

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

We notice that the proposed optimal FEC rate allocation mechanism allows robust JPEG 2000 codestream streaming over mobile ah 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 $C/N \leq 14$ dB which corresponds to PER $\leq 9.9 \times 10^{-2}$, the dynamic FEC rate allocation presented in [14] outperforms the layered UEP scheme proposed by Guo et al. [13]. However, for both schemes the peak signal-to-noise ratio is still bellow 30 dB, 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 $\leq$ 25 dB).

For noisy channel, typically $14\,\text{dB} < C/N \leq 18$ dB, the proposed optimal FEC rate allocation scheme performs from 4 dB to 11 dB more than layered UEP and from 9 dB to 13 dB 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 18 dB $< C/N \leq$ 20 dB, 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 in terms of PSNR.

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 35 dB 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 visualization 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 layer-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 transmission 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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