Scalable and Robust Wireless JPEG 2000 Images and Video Transmission with Adaptive Bandwidth Estimation

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***Abstract*— This paper presents a scalable and dynamic scheme for robust JPEG 2000 images/video transmission over wireless channels. The proposed system relies on an adaptive bandwidth estimation tool to select the suitable JPEG 2000 streams, layers and resolution. A Wireless JPEG 2000 (JPWL) compliant Forward Error Correction (FEC) scheme is introduced. An optimal layer oriented Unequal Error Protection Forward Error Correction rate allocation scheme is proposed to ensure codestreams protection against transmission errors. The main advantages of the proposed scheme are its optimality, its compliance to Wireless JPEG 2000 (the 11th part of JPEG 2000 standard) and its low time consumption. We demonstrate that our proposed scheme outperforms the layer oriented FEC scheme proposed by Guo *et al.* and other existing layer based FEC schemes. We also show that, due to its low run time, our layer based scheme is a good candidate for highly time constrained motion JPEG 2000 video streaming applications, thus, in this sense, its overcomes the limitation of optimal packet oriented FEC rate allocation scheme. We then validate the effectiveness of our proposed layer oriented scheme with a Wireless Motion JPEG 2000 client/server application.**

Keywords: layer-oriented FEC; unequal error protection; layer scalability; wireless JPEG 2000; video streaming

I. INTRODUCTION

In high error rate environments such as wireless channels, data protection is mandatory for efficient transmission of images and video. In this context, JPEG 2000, the newest image representation standard [1] proposes in its 11th part (Wireless JPEG 2000 – JPWL) [2] different techniques such as data interleaving, FEC with Reed-Solomon (RS) codes etc. in order to enhance the protection of JPEG 2000 codestreams against transmission errors.

Since wireless channels' characteristics depend on the transmission environment, the packet loss rate in the system also changes dynamically. Thus a priori FEC rate allocation schemes such as the one proposed in [3] are less efficient.

Moreover, in wireless multimedia systems such as the one considered in this paper (see Figure 1), a straightforward FEC methodology is used, by applying FEC uniformly over the entire stream (Equal Error Correction - EEP). However in [4], Gupa et al. suggest that for hierarchical codes, such as JPEG 2000, Unequal Error Protection (UEP) which assigns different FEC to different portion of codestream has been considered as a suitable protection scheme.

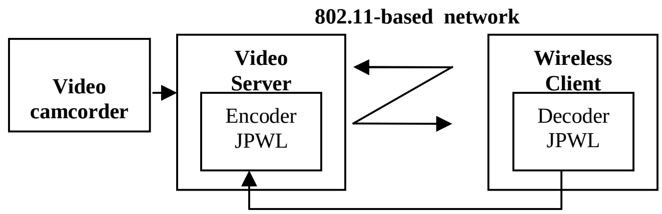

Figure 1. Wireless video streaming system

Two families of data protection schemes address this issue by taking the wireless channel characteristics into account in order to dynamically assign the FEC rate for JPEG 2000 based images/video. The first family is based on a dynamic layer-oriented unequal error protection methodology whereas the second relies on a dynamic packet-oriented unequal error protection methodology. Hence, in the first case, powerful RS codes are assigned to the most important layers and less robust codes are used for the protection of less important layers. It is worth noting that in this case, all the JPEG 2000 packets belonging to the same layer are protected with the same selected RS code. Examples of layer-oriented FEC rate allocation schemes are available in [4] and [5]. On the other side, in packet-oriented FEC rate allocation schemes such as the one presented in [6], RS codes are assigned in descending order of packets importance. In [6], we demonstrate that the proposed optimal packet-oriented FEC rate allocation is more efficient than the layer-oriented FEC rate allocation scheme presented in [4] and [5]. However, layer-based FEC rate allocation schemes have low complexity while packet-oriented FEC allocation methodologies are complex especially when the number of packets in the codestream is high. In this case, packet oriented FEC schemes are unpractical for highly time-constrained images/video streaming applications. Therefore, switching to a layer oriented FEC rate allocation scheme is more interesting. The smart FEC rate allocation scheme proposed in [7] addresses this issue by allowing switching from a packet oriented FEC scheme to a layer oriented scheme such as the ones proposed in [4] and [5]. However, to our knowledge, existing layer oriented FEC rate allocation schemes are based on heuristics and thus are suboptimal because they rely on parameters which are empirically fixed. For example, the layer oriented FEC scheme proposed in [4] relies on the permissible error rate (θ) whereas the layer oriented FEC scheme proposed in [5] relies on a Quality of Service (QoS) metric (ε_0).

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In this paper, based on the optimal packet oriented FEC methodology presented in [6], we propose an optimal layer oriented FEC rate allocation scheme for robust JPEG 2000 codestreams transmission over wireless channels.

The paper is organized as follows. In Section II, an overview of the video streaming system and a presentation of layer based FEC rate allocation schemes are provided. In Section III and IV, we describe the optimal layer oriented FEC scheme and the available bandwidth estimation scheme. We show the performances achieved by our proposed layer based FEC scheme in Section V. Finally, some conclusions are drawn in Section VI.

II. Overview Of The Streaming System And Of The JPEG 2000 Based FEC Rate Allocation Schemes

This section is dedicated to the description of the considered wireless JPEG 2000 video streaming system and to the presentation of existing FEC rate allocation schemes.

A. The Wireless JPEG 2000 video streaming system and the wireless channel

Unlike the system described in [6], where the FEC rate allocation scheme is packet oriented, in the current paper we consider a layer oriented FEC rate allocation scheme. In other words the difference between both systems is the FEC rate allocation module. In the packet oriented scheme the redundancy is added by taking the packets importance into account (see Figure 2) while in our layer oriented scheme, we rely on layer importance in order to allocate the adequate RS codes (see Figure 3).

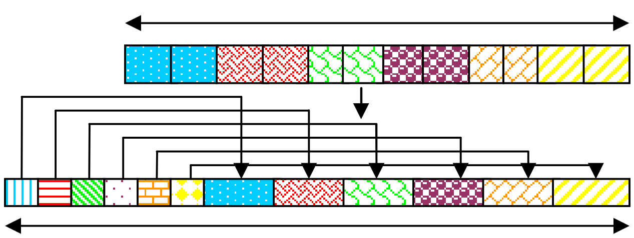
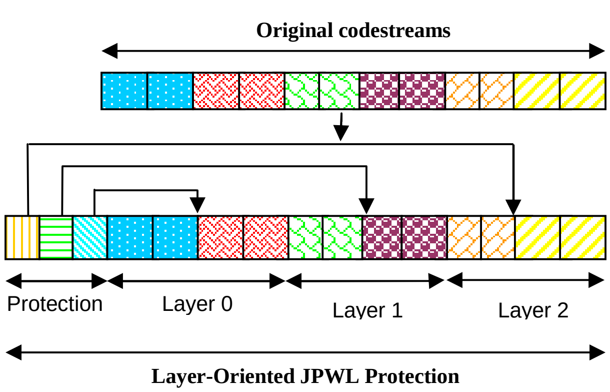


Figure 2. A JPEG 2000 codestreams transmission through the JPWL packet-oriented FEC rate system



Figue 3. A JPEG 2000 codestreams transmission through the JPWL layer-oriented FEC rate system

The wireless channel is emulated by real wireless channel traces available in [13]. At the encoder side, the Gilbert model [14] is used to derive application level models of error occurrences in the considered traces. A detailed description of the platform used to generate the loss patterns along with an analysis on wireless channel modeling with Gilbert model is provided in [6].

B. Overview of JPEG 2000 based FEC rate allocation schemes

In this section we present an overview of JPEG 2000 based FEC schemes.

1) Packet-oriented FEC rate allocation scheme

In this FEC rate allocation scheme the correct decoding of packet i at the receiver yields a reduction of the distortion on the transmitted image. Since $RD_{i,\gamma}$ is considered as the reduction of distortion achieved when packet i is protected at the level γ, the gain is the ratio between the image quality improvement $RD_{i,\gamma}$ and the associated cost in terms of bandwidth consumption.

For each JPEG 2000 image, the optimal packet-oriented algorithm models the channel with a Gilbert model and for each possible protection level γ, its evaluates the probability of incorrect word decoding. Then, for each packet i, based on the estimated probability of decoding word, the reduction of distortion associated with the decoding of packet i, protected from level γ to $\gamma_{\max}$ is estimated. The gain yield by the associated increment of quality is also computed. After ordering those gain values by decreasing order of importance, the optimal protection rate for each packet is selected up to meet the rate constraint.

2) Layer-oriented FEC rate allocation scheme

In layer-oriented FEC rate allocation schemes ([4] and [5]), unequal error protection is applied by taking the importance of each layer into account. Those families of FEC rate allocation schemes can be divided in two groups: non JPWL compliant schemes and JPWL compliant schemes.

a) Non JPWL compliant Layer-oriented FEC rate allocation scheme

In non JPWL compliant layer-oriented FEC rate allocation schemes such as the one presented in [4], the slope of the Rate-Distortion curve is used to select a code for each quality layer. The slope S_j corresponding to layer j is expressed as: $S_j = \Delta D_j / \Delta R_j$ where, S_j represents the contribution of layer j to the improvement of image quality, ΔR_j is its length (in byte) and ΔD_j corresponds to the distortion decrement measured by MSE (Mean Square Error).

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Hence powerful non JPWL compliant RS codes are set to the most important layers such as the base layer and the other layers are protected by decreasing order of importance. 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 sequences. Moreover, the algorithm proposed by Z. Guo *et al* was not adaptive. In this work, we overcome this limitation by adapting the Z. Guo algorithm for a dynamic selection of RS codes thanks to a dynamic Bit Error Rate (BER) estimation scheme.

b) JPWL compliant dynamic Layer-oriented FEC rate allocation scheme

JPWL compliant FEC rate allocation schemes, such as the one presented in [5], are based on the assumption that transmitted JPEG 2000 image quality is linked to the amount of correctly decoded packets at the receiver. Hence, goal of this scheme is to maximize the overall throughput in the system under a Quality of Service (QoS) fixed parameter (ε_0). The dynamic layer-oriented FEC rate allocation scheme improves the performance by about 10% compared to a priori selection of channel coding.

The layer oriented FEC rate allocation schemes presented in this section are characterized by heuristics whose parameters are set in order to achieve a desired Quality of Service. Hence, high QoS level means more data protection and thus more bandwidth consumption. Since wireless client/server systems are bandwidth constrained, the desired high QoS level may not be achieved because of the risk of exceeding the available bandwidth. In this sense, traditional layer based FEC rate schemes may be viewed as suboptimal as they achieve a less effective codestreams protection. The proposed optimal layer oriented FEC rate allocation scheme overcomes these limitations by selecting the best RS codes yielding by this way the maximum achievable images/video quality regarding the available resources in the system.

III. Optimal Layer Oriented Forward Error Correction Rate Allocation

A. Layer Based FEC rate allocation problem formalization

Considering that JPEG 2000 codestreams are constituted of a set of L layers, the optimal FEC allocation problem can be resumed by answering the question: how to optimally protect each layer in order to minimize the transmitted image distortion under a rate constraint determined by the available bandwidth in the system?

Let B_{av} be the budget constraint in bytes corresponding to the available bandwidth in the system. Let lay_i be the length in bytes of the i^{th} layer of the L layers available in the codestream 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 inverse of the channel coding rate, so $(lay_i) \times fec$ represents, in bytes, the increase of the i^{th} layer length when protected at a level γ .

Unlike the packet oriented FEC scheme, where all the 16 default RS codes, defined by JPWL standard, are considered in the FEC rate allocation process, here we restrict the considered RS codes to those with $fec \le 2$. In other words we consider only the first 10 default codes. This assumption makes sense in the context of layer oriented FEC rate allocation, because adding redundant data which in ratio is more than twice superior to the original layers may overload the networks and drastically increase the losses instead of reducing them.

Let γ be a layer protection level selected in the range $0 \le \gamma \le \gamma_{\max}^{lay}$, each protection level corresponding to a specific RS code selected between the 10 JPWL default RS codes ($\gamma = 0$ means that the layer is not transmitted, $\gamma = 1$ means transmission with protection level 1, higher values imply increasing channel code capacity with γ and $\gamma_{\max}^{lay} = 10$).

Let β_i be the number of data packet constituting the i^{th} quality layer of a JPEG 2000 codestream, $RD_{lay_i}^{0}$ and $RD_{lay_i}^{\gamma}$ be respectively the reduction of distortion associated to the correct decoding of layer i and the reduction of distortion associated to the correct decoding of layer i protected to level γ . The reduction of distortion metric associated to the correct decoding of the packets of a JPEG 2000 codestream is extracted from a codestream index file. The reduction of distortion metric is further presented in [6]. We rely on this codestream index file to derive $RD_{lay_i}^{0}$ and we associated the decoding error probability estimation process presented in [14] in order to derive $RD_{lay_i}^{\gamma}$. Hence, the layer oriented FEC rate allocation problem is formalised by:

$$\text{Maximize} \quad \sum_{i}^{L} \frac{RD_{lay_i}^{\gamma}}{(lay_i) \times fec_i} \qquad (3\text{-}1)$$

$$\text{Subject to} \quad \sum_{i}^{L} (lay_i) \times fec_i \le B_{av} \qquad (3\text{-}2)$$

We addressed this problem in [18] by proposing an optimal layer oriented FEC rate allocation scheme. In the following we present the proposed algorithm.

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B. Optimization

We define $G_{lay_i}^{\gamma}$ as the gain in quality of the transmitted image obtained at the receiver side when layer i is decoded.

We derive $RD_{lay_i}^{1}$ and $RD_{lay_i}^{\gamma}$ the reduction of distortion obtained when layer i is transmitted respectively with protection level 1 and with protection level γ .We have:

$$RD_{lay_i}^{1} = (1-P_{lay_i}^{1}) \times RD_{lay_i}^{0}$$
$$RD_{lay_i}^{\gamma} = (1-P_{lay_i}^{\gamma}) \times RD_{lay_i}^{0} \quad (3\text{-}3)$$

where $P_{lay_i}^{1}$ and $P_{lay_i}^{\gamma}$ are the decoding error probabilities obtained when layer i is protected respectively to level 1 and to level γ . The final gain is:

$$G_{lay_i}^{1} = \frac{RD_{lay_i}^{1}}{lay_i} = \frac{(1-P_{lay_i}^{1}) \times RD_{lay_i}^{0}}{lay_i} \quad (3\text{-}4)$$

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

$$G_{lay_i}^{1} = \frac{RD_{lay_i}^{\gamma} - RD_{lay_i}^{\gamma-1}}{(fec_{\gamma} - fec_{\gamma-1}) lay_i}$$
$$G_{lay_i}^{\gamma} = \frac{(P_{lay_i}^{\gamma-1} - P_{lay_i}^{\gamma}) RD_{lay_i}^{0}}{(fec_{\gamma} - fec_{\gamma-1}) \times lay_i} \quad (3\text{-}5)$$

For each layer, a set of gain values is computed, ordered in decreasing order of importance and stored in a vector. Then, the FEC rate associated to the first gain value of each vector is applied for the corresponding layer's protection without exceeding the available bandwidth. It is worth noting that all the packets belonging to the same layer are protected at the same FEC rate.

C. Contribution of the proposed optimal layer oriented FEC rate allocation scheme

Even if the gain metrics presented in the previous section seem close to the ones used in [6], they hold a fundamental difference because they rely on the contribution of each layer to the reduction of distortion instead of just taking into account the contribution of a specific packet. Actually, during the source coding process, the incremental contribution from the set of image codeblocks is collected in quality layers. Due to the fact that the rate-distortion compromises derived during JPEG 2000 truncation process are the same for all the codeblocks, for any quality layer index i the contributions of quality layer 1 through quality layer i constitute a rate-distortion optimal representation of the entire image. Hence, at layer level the reduction of distortion values are strictly decreasing. In contrast, the selection of a specific JPEG 2000 packet does not guarantee that the contributions of packet 1 to the selected index packet are monolithically decreasing. In this case, as confirmed by A. Descampe *et al* [15], some additional restrictions have to be added to the considered convex-hull in order to ensure rate-distortion and cost-distortion optimality. This justifies the necessity to have a merging step in the packet oriented FEC scheme [6] (it ensures that the convex-hull is always convex). In the layer oriented FEC this step is skipped because the reduction of distortion curve is already monolithically decreasing, significantly reducing the complexity and thus the time-consumption of the FEC rate allocation algorithm. Moreover, in the proposed optimal layer oriented FEC scheme, we only consider the first 10 RS codes instead of considering all the 16 default RS codes defined by JPWL standard as it is the case in [6]. This also reduces considerably the FEC scheme time consumption as its leads to less gains values computation which make the proposed optimal layer FEC rate allocation scheme a good candidate for real time images/video streaming applications.

In addition, the number of layers available in the codestreams is another criterion which contributes to the reduction of the time consumption of our proposed FEC scheme. Actually, a JPEG 2000 image extracted from a Motion JPEG 2000 video sequence is defined by (L, R, C) where L is the number of quality layers of the considered image , R is its resolution level corresponding to the decomposition levels of the Discrete Wavelet Transform and C is the number of components. Assuming that the considered JPEG 2000 image is not spatially divided and thus is described by a unique tile, the number of data packets available in the considered JPEG 2000 codestreams is given by $S = L \times R \times C$. In this context, the complexity of packet oriented FEC schemes [6] is based on the S data packets while the complexity of the optimal layer based FEC is based on the L layers available in the codestreams. In scalable JPEG 2000 images, since the number of layers is significantly lower in comparison to the number of data packets, the time consumption of our proposed layer oriented FEC scheme is significantly low in comparison to packet oriented scheme.

Algorithm:

For each JPEG 2000 image

- Model the channel with a Gilbert model and for each possible protection level γ ($0 \le \gamma \le 10$), evaluate the probability of incorrect word decoding $P_{lay_i}^{\gamma}$

- For $i=1$ to $i=L$ (Number of JPEG 2000 layers)

  For $\gamma = 1$ to $\gamma = 10$

  Estimate $RD_{lay_i}^{\gamma} = (1-P_{lay_i}^{i,\gamma}) \times RD_{lay_i}^{0}$

  $$G_{lay_i}^{1} == \frac{RD_{lay_i}^{\gamma} - RD_{lay_i}^{\gamma-1}}{(fec_{\gamma} - fec_{\gamma-1}) lay_i}$$

  End For

End For

- Order gain values in decreasing order of importance
- Select each gain value, corresponding to a specific protection level, up to meeting the rate constraint
- Optimally protect JPEG 2000 layers with the corresponding RS codes

End For

IV. BANDWIDTH ESTIMATION AND IMAGES/VIDEO SCALABILITY SCHEME

A. *Available Bandwidth estimation*

In the literature many authors investigate classifications of the bandwidth estimation tools. In [7], R. Prasad et al. define four types of bandwidth estimation tools. The first one, the Variable Packet Size technique (VPST) measures the capacity of individual hops. It uses ICMP (Internet Control Message Protocol) packets to measure the RTT (Roundtrip Time). It assumes that the minimum RTT means no queuing delays. Hence queuing delays are not taken into account to estimate capacity. The result is a straight line, whose slope equals 1/C. The second bandwidth estimation tool presented in [7] is the Probing Packet Pair Dispersion Technique (PPPDT) which measures the end-to-end capacity using a packet pair with the same length and rate. The capacity is found using the formula:

$$C = \frac{L}{\Delta_{out}}$$

where Δ_{out} is the dispersion of the packet pair at the receiver.

The third bandwidth estimation tool is the Self-loading Periodic Streams Technique (SLoPST) which measures the available bandwidth sending packet with the same length but at different rates and calculating its one way delay. The moment the delay starts to increase means the available bandwidth has been exceeded.

The last bandwidth estimation tool is the Probing Packet Pair Trains Dispersion Technique (PPPTDT) which measures the available bandwidth and the capacity of an end-to-end path. It sends a train of packet pairs at gradually increasing packet rate and estimates its average dispersion rate at the receiver. The result is a curve where the slope is 1/C and the inflexion point is the available bandwidth value.

In our work, we focus on a fast bandwidth estimation technique because it is more effective in tracking fast varying wireless channels like the ones considered in our scenarios.

B. *Available Bandwidth estimation tool*

The available bandwidth estimation tool which is implemented in our system is called WBest (Bandwidth Estimation Tool for Wireless Networks) and is presented in [8] by M. Li and C. Chang. It is a two step fast converging and accurate bandwidth estimation tool. It uses the effective capacity (C_e) to estimate the available bandwidth. It takes also into account cross-traffic impact. First, the effective capacity is measured using an improved Probing Packet Pair Technique. Actually, in this technique, the median of the dispersion of the train of packet pairs sent is calculated. Then, another packet train is sent at the rate of the effective capacity in order to evaluate the real available bandwidth. This procedure avoids the additional delay which is yielded by the incremental packet rate generated while seeking for the rate which congests the path.

In this context, the available bandwidth (AB) is derived as follows:

$$AB = C_e\left(2 - \frac{C_e}{\Delta_{out}}\right) \text{ if there is no congestion}$$

$$\text{or } AB = 0 \text{ if congestion is detected}$$

It is worth noting that during the second step, congestion is detected by analyzing the dispersion of the packet train. If the dispersion is lower than $C_e / 2$, it means that congestion occurred. In this case, the bandwidth estimation process is cancelled because packets are queuing.

The authors of this work pointed out that finding the optimal lengths of the trains used in both stages is a difficult issue, and in [8], they propose a methodology to address this issue. Relying in the methodology proposed in [8], we empirically derive that in our scenarios, 6 packets pairs for the first train and 30 packets for the second train is a good tradeoff which yields sufficiently accurate bandwidth estimation results.

Once the available bandwidth estimated in our system, the following step consists in adapting the images and video streams to the channel conditions.

In the present work we implement an adaptive bandwidth estimation tool and propose an additional scalability tool at the encoder which dynamically and efficiently selects the best resolution and layer for each JPEG 2000 frame before transmission through the wireless channel. Hence, according to the estimated bandwidth, refinement layers could be added or removed from JPEG 2000 codestreams. We present in the following the processes which are implemented at the encoder.

Algorithm:

Once connected, the server starts the WBest [8] process in order to obtain the initial available bandwidth. At this step the goal is to send images and video with maximum detail (highest resolution and all refinement layers) matching with the estimated bandwidth. The original resolution and number of layers for the considered video is found using an indexer like the one available in [9].

In our work, the default number of resolution is 6, the length and the width of the image must be a power of 2 (here 352x288) and the number of layers is 3.

Let l be a layer of a JPEG 2000 image and SE^l_{rate} is corresponding source encoding rate. Let $fec^l_{rate} = \frac{n}{k}$ be the inverse of the Reed-Solomon code RS(n,k) selected by the layer oriented FEC rate allocation scheme to protect layer l against transmission errors. Let $frame\_length$ be the amount of data needed to transmit layer l protected, we have:

$$frame\_length = H \times W \times SE^l_{rate} \times fec^l_{rate} \qquad (4\text{-}1)$$

Since quality is the most important parameter for a JPEG 2000 transmission system, in our algorithm, for a given resolution we try to transmit a maximum number of refinement layers.

The proposed scheme is able to adapt to channel variations thanks to the bandwidth estimation tool. Hence, when the channel experiences good conditions, our heuristic algorithm selects the highest resolution with the highest quality (all the refinement layers are transmitted). If the channel experiences harsh conditions, image layers and resolution are decreased up to defined thresholds. We empirically derive thresholds ($l_{\max}/2$) for layer removing and for ($resol_{\max}/l_{\max}$) resolution reduction because we notice that images quality starts to show a huge degradation when we remove more than half of the original image layers and image visualization becomes impossible under this resolution reduction threshold. Hence, when the channel experienced bad conditions, image layers are incrementally reduced while maintaining original resolution of the JPEG 2000 frame to highest level. However, if the corresponding frame length do not match the available bandwidth, image resolution downscaling is done. It is worth noting that our fixed thresholds are valid for our scenarios and may change in different environments.

Once the resolution and the number of layers are chosen, the server sends the video streaming to the client.

The available bandwidth estimation tool is launched every 10 frames but this frequency could be changed according to the application requirements. An interesting extension to this work could be to optimally adapt the frequency of the bandwidth estimation tool to the channel conditions.

The efficiency of the proposed heuristic algorithm is demonstrated using a wireless client/server video streaming application. In the following section, we present the results derived from different video streaming scenarios.

C. Results of Available Bandwidth estimation

The video streaming scenarios considered in this work are derived from wireless transmission trials used in the literature for bandwidth estimation purpose.

The video sequence is speedway.mj2 [16] which is a 352x288 motion JPEG2000 sequence constituted of 200 JPEG 2000 frames with six resolutions and three layers each.

1) Scenario 1

In the first scenario, the wireless channel considered is derived from BART tool [10], which estimates the available bandwidth in an end-to-end path where the bottleneck is a wireless hop. It uses the Probing Packet Pair Trains Dispersion Technique and improves the system using Kalman filters to measure and track the changes.

In this scenario, we focus on the fast varying part of the estimated bandwidth. Moreover, we divide the bandwidth estimated by BART tool [10] by a parameter δ=2 in order to show that our scheme is efficient even when the wireless channel experienced harsh conditions.

Heuristic

1-Wait for client connection request

2-Estimate available bandwidth (B_{av}) using WBest tool

3-Derive original images/video maximum number of layers ($l_{\max}$) and maximum resolution ($resol_{\max}$) from the indexer

For each JPEG 2000 image:

4-Initialize current layer parameters ($cur\_lay = l_{\max}$) and current resolution ($cur\_resol = resol_{\max}$)

5-Calculate the needed bandwidth B_{needed}

$$B_{needed} = \sum_{i=1}^{cur\_lay} cur\_resol \times SE^{i}_{rate} \times fec^{i}_{rate}$$

6- While ($cur\_lay > l_{\max}/2$)

```
{
  If (B_av ≥ B_needed) Send Image

  Else
  {
    cur_lay = cur_lay − 1
    Calculate B_needed = Σ_{i=1}^{cur_lay} cur_resol × SE^i_rate × fec^i_rate
  }
}
Else
{
    While (cur_resol > resol_max / l_max)
    {
      cur_resol = cur_resol / 2
    Calculate B_needed = Σ_{i=1}^{cur_lay} cur_resol × SE^i_rate × fec^i_rate
    If (B_av ≥ B_needed) Send Image
    Else
      { cur_resol = cur_resol / 2
        cur_lay = cur_lay + 1
      }
    }
}
```

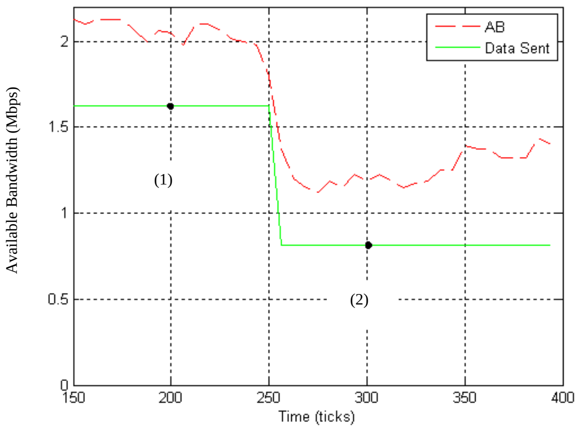

Figure 4.a Available bandwidth versus time – BART Tool scenario

Speedway10.j2k

Speedway25.j2k

Figure 4.b Images processed at point (1) and (2) - BART Tool scenario

Scenario 1	Image Length	Image Width	Layer of transmitted Images
(1)	352	288	3
(2)	352	288	2

Table 1: Scalability parameters - BART Tool scenario

In figure 4.a, point (1) indicates that the estimated bandwidth is higher than the needed bandwidth, hence initial JPEG 2000 frames are transmitted. Point (2) shows that the estimated bandwidth is decreased and becomes insufficient to send original images. Hence, the algorithm maintains the resolution at the highest level (initial value) but one layer is removed from original frames as shown in Table 1.

In Figure 4.b we randomly select and present images speedway10.j2k and speedway25.j2k which have been processed respectively on points (1) and (2).

2) Scenario 2

The second scenario is derived from the work of Gupta et al. [11]. In their work, their compare a passive technique that uses packets containing useful data as probing packets and the pathchirp tool which is a general bandwidth estimation tool designed using Self-loading Periodic Streams (SLoPS). They demonstrated that the passive tool follows more accurately the changes of the available bandwidth. Moreover, they show that saturating the network to estimate the bandwidth is not the best choice.

In this scenario, the network is a single link between two computers with two additional cross-traffics. The estimated bandwidth has been divided by δ=7 in our tests.

In figure 5.a we observe three points corresponding to different available bandwidth along with adapted data rate. Point (1) indicates that the available bandwidth is significantly low compared to the needed bandwidth. In this case resolution is downscaled without removing a quality layer. Then point (2) shows that when the available bandwidth is increased, resolution is up-scaled while removing a quality layer. Finally, original frames are transmitted at point (3).

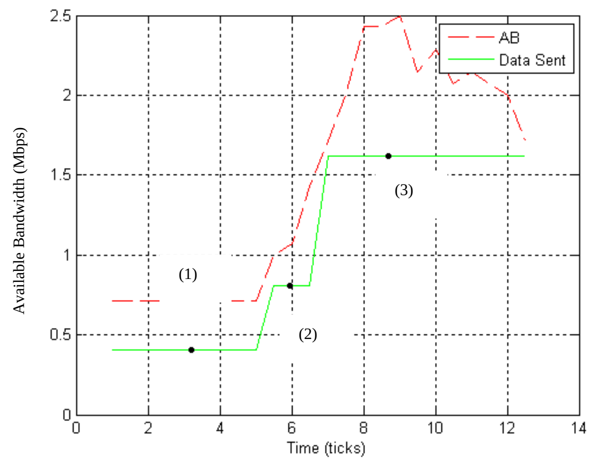

Figure 5.a Available bandwidth versus time – Pathchirp tool scenario

Speedway5.j2k

Speedway13.j2k

Speedway18.j2k

Figure 5.b Images processed at point (1), (2) and (3) - Pathchirp tool scenario

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Scenario Pathchirp tool	Image Length	Image Width	Layer of transmitted Images
(1)	176	144	0
(2)	352	288	1
(3)	352	288	0

Table 2: Scalability parameters - Pathchirp tool scenario

In the following, instead of using pathchirp tool for bandwidth estimation, we use a passive tool which is a more accurate tool [11]. Results are presented in Figure 6.a. For the same scenario, we notice that one additional bandwidth state is detected in point (4) which demonstrates that the passive tool is more accurate than pathchirp tool

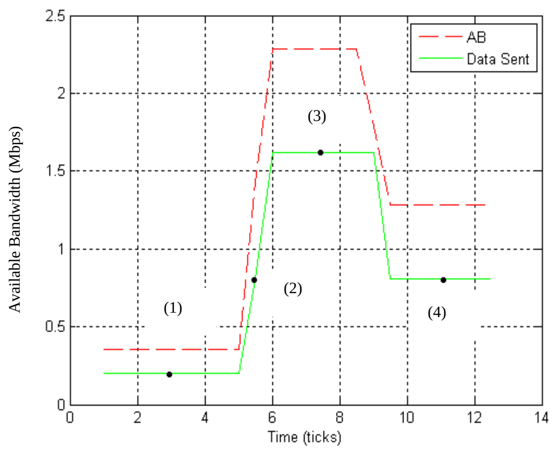

Figure 6.a Available bandwidth versus time – Passive tool scenario

Speedway5.j2k

Speedway10.j2k

Speedway14.j2k

Speedway20.j2k

Figure 6.b. Images processed at point (1), (2), (3) and (4) - Passive tool scenario

In comparison to the pathchirp tool, using the passive tool yields image quality layer downscaling at point (4) instead of maintaining the transmission of unmodified original images (see Table 3). Hence, using pathchirp tool may lead to networks overloading.

Scenario Passive tool	Image Length	Image Width	Layer of transmitted Images
(1)	176	144	1
(2)	352	288	1
(3)	352	288	0
(4)	352	288	1

Table 3: Scalability parameters - Passive tool scenario

Figure 6.b presents speedway5.j2k, speedway10.j2k, speedway14.j2k and speedway20.j2k which have been processed respectively on points (1), (2), (3) and (4).

V. PERFORMANCES OF THE OPTIMAL LAYER ORIENTED FEC RATE ALLOCATION SCHEME

A. *Performance of layer based FEC scheme in terms of time consumption*

In Figure 7 the run time of the proposed layer based FEC rate allocation scheme is plotted versus the number of data packets available in the JPEG 2000 codestreams. This curve is compared to the one achieved using the optimal packet oriented FEC rate allocation scheme [6]. These results are achieved using an Intel core Duo CPU 2.9 GHz workstation.

As packet-oriented and layer oriented schemes are linked by the number of layers available in each image, we vary this parameter in order to derive some comparable results. In the considered scenario, the number of available resolution and component of JPEG 2000 frames are fixed (resolution = 10 and component = 1) because these parameters do not impact the time-performance of layer oriented FEC rate allocation schemes. In Figure 7 each packet (i) corresponds to a specific JPEG 2000 frame (with a specific quality layer).

In this scenario, the available bandwidth in the system is set to 18 Mbit/s ($B_{av} = 18\,Mbits/s$). It is worth noting that in practice few existing JPEG 2000 codecs allow high quality scalability and to our knowledge, none of them can handle more than 50 quality layers. Hence, the considered scenario allows generalization to future high quality layer scalable FEC rate allocation systems.

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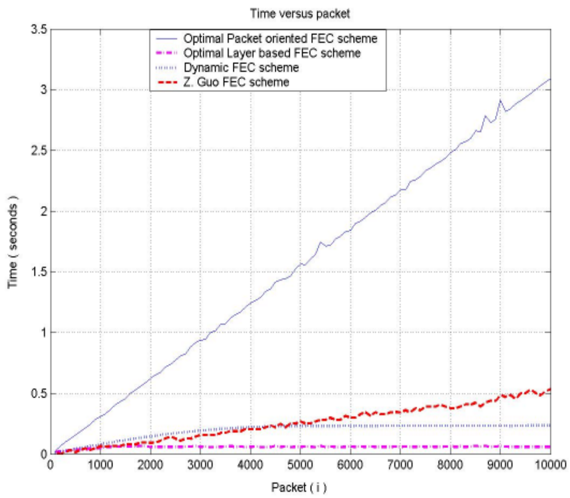

Figure 7. Time versus packets: Fixed image resolution (R=10) –Varying quality layers (0 to 100) – One component (C =1)

In Figure 7 we notice that both layer and packet oriented scheme have a run time linearly increasing with the number of packets available in the codestreams. However, the optimal layer based FEC scheme is significantly less time consuming than the packet based FEC scheme. For codestreams containing less than 1000 packets (quality layers $\leq$ 10) the packet oriented FEC scheme is 3 times more time consuming than our optimal layer based FEC scheme. For JPEG 2000 codestreams, whose number of packets is between 1000 and 5000 (quality layers between 10 and 50) the packet oriented scheme is up to 5 times the run time of the layer based FEC scheme. Since existing JPEG 2000 codecs handle less than 50 quality layers, our proposed optimal layer based scheme is a good candidate for real-time JPEG 2000 codestreams over wireless channel as its yields low time consumption. For codestreams with a number of packets between 5000 and 10000 (quality layers between 50 and 100 – high layer scalability) the packet oriented scheme has 6 times the run time of the layer based FEC scheme. Hence, our proposed layer based scheme, due to its low time consumption, could be viewed as a good candidate for future high quality layer scalable wireless JPEG 2000 based images and video streaming applications.

Although our proposed scheme achieves good performances in terms of time consumption in comparison to packet oriented FEC rate allocation schemes, the last ones present better performance in terms of visualization quality especially for highly noisy channels. It is worth noting that packet oriented and layer oriented FEC schemes advantages could be combined in a smart switching FEC rate allocation scheme such as the one proposed in [12].

In the following section we demonstrate the effectiveness of our proposed layer based FEC scheme thank to a client/server application of Motion JPEG 2000 video streaming over real ad-hoc network traces.

B. Layer oriented FEC rate allocation for Motion JPEG 2000 video streaming over real ad-hoc network traces

In this section we present the results achieved while streaming Motion JPEG 2000 based video over real ad-hoc network channel traces [13] and we demonstrate that the proposed optimal layer based scheme outperforms existing layer oriented FEC schemes even if for highly noisy channels it is less efficient than packet oriented FEC scheme. The comparison is handled both in terms of Structural Similarity (SSIM) [17] and in terms of successful decoding rate. We derive the Mean SSIM metric of the Motion JPEG 2000 video sequence by averaging the SSIM metrics of the JPEG 2000 images contained on the considered video sequence. It is worth noting that each SSIM measure derived is associated to a successful decoding rate metric which corresponds to decoder crash avoidance on the basis of 1000 transmission trials.

The considered wireless channel traces are available in [13] and the video sequence used is *speedway.mj2* [16] 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.

Figure 8 presents the successful decoding rate of the motion JPEG 2000 video sequence *speedway.mj2* [16] transmission over real ad-hoc network channel traces [13]. We observe that for highly noisy channels ($C/N \leq 15\ dB$), the proposed optimal layer outperforms other layer based FEC schemes but is less efficient than the packet oriented scheme. For noisy channel ($15\ dB \leq C/N < 18\ dB$), we notice that all layer based UEP schemes exhibit similar performances in terms of successful decoding rate. However, for low noisy channels ($C/N \geq 18\ dB$) all the FEC schemes yield the same improvement in terms of successful decoding rate.

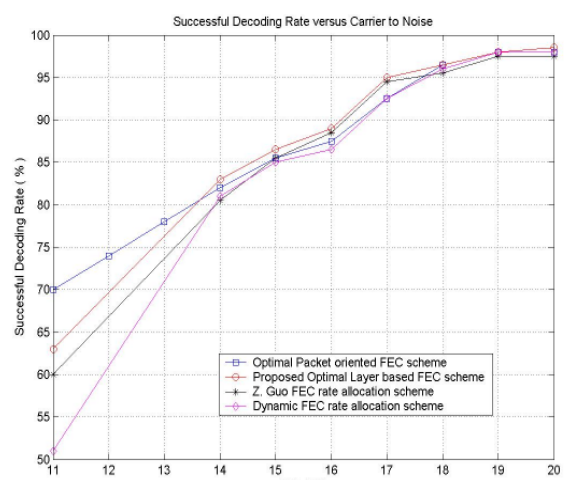

Figure 8. Successful decoding rate versus Carrier to Noise Ratio

In Figure 9 we show that our proposed optimal layer based FEC rate allocation scheme still outperforms other layer based schemes in terms of Mean SSIM. This is due to the fact that the base layer which is the most important part of the codestreams is highly protected in our proposed scheme, in comparison to other layer based schemes, guaranteeing this way a good quality for the visualization.

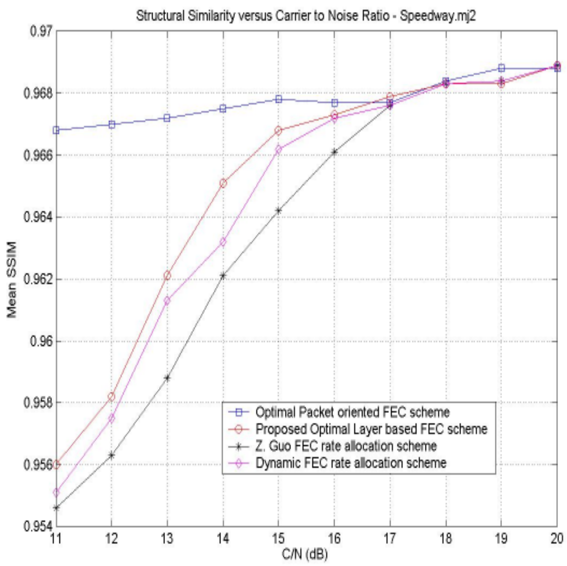

Figure 9. Mean Structural Similarity versus Carrier to Noise Ratio

It is worth noting that, for highly noisy channels, our optimal layer oriented FEC scheme is less efficient than optimal packet oriented FEC scheme presented in [6]. However the last one is unpractical for real time streaming applications when the number of packets in the codestreams is high. In contrast our proposed layer oriented efficiently overcomes this limitation. In this context, instead of being used to replace packet oriented FEC rate allocation schemes, our proposed optimal layer based FEC scheme should be used to complete it. Thus, an interesting extension to this work could be to consider the framework of unifying both families (packet oriented and layer oriented) and going straightforward to derive an optimal combined packet/layer oriented FEC rate allocation scheme for robust transmission of JPEG 2000 images/video over wireless channels.

VI. Conclusion

In this paper we presented an optimal layer oriented FEC rate allocation scheme for robust JPEG 2000 images/video streaming over wireless channels. Compared to packet oriented FEC schemes, our proposed layer based scheme is significantly less time consuming while offering similar performances in terms of Structural Similarity for low noisy channels. However, for highly noisy channels, the packet oriented scheme is more efficient than the proposed scheme which leads us to the conclusion that both packet oriented and layer oriented schemes should not be viewed as antagonists FEC schemes, but should be combined in a new framework of combined packet/layer based FEC rate allocation scheme. In this context, our proposed optimal layer oriented scheme is a good candidate for both highly constrained video streaming applications and for future unified packet/layer based FEC rate allocation schemes.

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