Unequal Power Allocation for Transmission of JPEG2000 Images over Wireless Channels

Mahin Torki and Atousa Hajshirmohammadi
School of Engineering Science, Simon Fraser University
Burnaby, BC, Canada, V5A 1S6
Email: mta33@sfu.ca, atousah@sfu.ca

Abstract—In this paper, we present an unequal power allocation method that exploits the hierarchical structure of JPEG2000 coded bitstream, along with the channel state information, to assign different transmission powers to different parts of the bitstream at the coding pass level. Based on the information from the JPEG2000 bitstream, we first develop a distortion model to evaluate the distortion of the reconstructed image in terms of the power assigned to each coding pass within the bitstream. Using this model and the channel information, the powers are calculated such that the distortion of the decoded image is minimized. Simulation results show up to 7 dB improvement in the decoded image quality compared to the case of equal power allocation and up to 4 dB enhancement compared to the state-of-the-art methods proposed for the transmission of JPEG2000 streams over wireless channels.

I. INTRODUCTION

Robust transmission of scalable image and video contents over wireless channels has received much attention in recent years. However, inherent unreliability of the wireless channels, which suffer from fading and interference, makes achieving robust wireless communications a challenging task. On the other hand, scalable bitstreams are more prone to channel errors than plain data bitstreams. Due to the entropy coding employed in scalable bitstreams, even a single bit error in the encoded image can cause error propagation and affect large image areas, resulting visible and often objectionable image quality degradation.

Unequal error protection (UEP) is one of the techniques appropriate for protecting scalable bitstreams against bit corruptions. The idea behind UEP is driven by the fact that different portions of scalable bitstream have different impact on the quality of the decoded image. The UEP scheme exploits the hierarchical structure of the scalable coded bitstream and assigns higher protection to the more important parts. Several UEP techniques have been proposed in the literature for efficient transmission of scalable bitstreams over wireless channels, which are based on assigning variable forward error correction (FEC) coding to different portions of the bitstream according to their importance.

In [1], a product code consisting of concatenated CRC/RCPC codes and Reed-Solomon codes is proposed for the protection of progressively coded images transmitted over wireless and memoryless channels. In [2], the method proposed in [1] is improved by reorganizing the source code into a set of independently decodable packets. In [3], a product coding scheme, including Reed-Solomon and Turbo codes, has been introduced for the transmission of JPEG2000 bitstreams over wireless channels. Their scheme provides unequal protection against both errors and erasures. The presented method in [3] outperforms the methods of [1] and [2] in terms of the decoded image quality.

Alternatively, UEP can also be achieved by means of unequal power allocation (UPA), i.e., using different transmission powers over the bitstream ([4][5]). In [4], a Hybrid FEC-UPA algorithm is proposed for transmission of JPEG2000 digital cinema streams over wireless channels. The bitstream is partitioned into several packets, which are protected by light FEC and transmitted through the channel at different powers. In this scheme, the authors assume that each packet can be decoded at the decoder only if all the previous packets have been correctly received, and the distortion is calculated based on this assumption. However, because of the independent decoding of codeblocks in JPEG2000 decoder, it is possible to refine this assumption by calculating the distortion at the coding pass level, as explained later in this paper. All of the above methods either employ error correction coding only, or a combination of coding and UPA, to enhance the quality of the received image. They use code rates in the order of 0.3. In [5], a UPA only algorithm for transmission of JPEG images over a MIMO system is proposed. There, the authors assume that the channel matrix is perfectly known at both the transmitter and the receiver.

In this paper, we focus on the transmission of JPEG2000 bitstreams over wireless channels using UPA only. For higher bandwidth efficiency and lower system complexity, we do not use any error correction coding. Instead, we take advantage of the inherent scalable properties of the JPEG2000 bitstream along with channel state information (CSI) to enhance the quality of transmitted image. Our proposed method exploits the structural information of the JPEG2000 encoded bitstream in the error-resilient mode of the standard when the RESTART/ERTERM option is enabled. Using this information, the algorithm assigns the appropriate amount of power at coding pass level, which to the knowledge of the authors has not been done before. In addition, the algorithm takes advantage of the CSI to further improve the quality of transmission. The low complexity of our system allows us to find the optimum UPA levels for different channel conditions. Simulation results show up to 7 dB improvement.
in reconstructed image quality compared to transmission with equal power allocation (EPA), and up to 4 dB improvement compared to the method presented in [3].

The rest of the paper is organized as follows. The proposed system is described in section II, followed by the proposed “optimized UPA” algorithm in section III. In section IV, we present the implementation of our algorithm and section V provides the simulation results. Finally, section VI, concludes the paper.

II. SYSTEM OVERVIEW

The general block diagram of the proposed system is shown in Fig. 1. The first part of the system includes the JPEG2000 encoder. The JPEG2000 encoder first divides the image into disjoint rectangular tiles. Wavelet transform is then applied to each tile to generate subbands, which are divided into rectangular-shaped precincts, and further divided into square-shaped codeblocks. Each bitplane of a codeblock is encoded by an arithmetic encoder in three coding passes. This provides a progressive bitstream for each of the codeblocks. Coding passes are then interleaved to create the scalable JPEG2000 bitstream. It is important to note that different coding passes have different impact in the quality of the decoded image. This impact is evaluated by the “structural information retrieval” unit as explained shortly.

To avoid error propagation, several error-resilient features are included in the JPEG2000 standard. Of particular interest to us is the RESTART/ERTERM mode, which creates a separate predictably terminated codeword segment for each coding pass. Any error in the bitstream is likely to leave the decoder in a state which is inconsistent with the predictable termination policy [6]. An error-resilient decoder is able to detect the existence of an error in the bitstream within three coding passes from where the error occurred in over 99% of the cases. Once an error is detected, the decoder discards the remaining coding passes up to the end of that codeblock.

The encoded image is passed on to the “structural information retrieval” block, which extracts the information required by the “optimized UPA” unit. This includes information such as the number of codeblocks in the bitstream and the number and lengths of coding passes within each codeblock. Furthermore, the UPA unit requires the information about the impact of each coding pass in the overall quality of the received image. We use the distortion (mean square error (MSE)) of the decoded image as the measure of this impact. To obtain this information, errors are induced in each coding pass, while the rest of the bitstream is left error free. We then measure the resulting distortion, \( D_{ij} \), which corresponds to coding pass \( j \) of codeblock \( i \) (\( CP_{ij} \)).

The “optimized UPA” and the “power adjustment” units, are the main parts of the proposed system, and are described in detail in Sections III and IV. Briefly however, these units use the channel information along with the information from the “structural information retrieval” unit to divide the total power allocated to the transmission of the image (\( P_{Total} \) in Fig. 1), unequally between different coding passes.

Finally the information bits are transmitted through the channel and decoded by the JPEG2000 decoder.

III. OPTIMIZED UPA

The proposed UPA scheme is driven by the fact that different parts of the JPEG2000 bitstream have different impact on the quality of the decoded image and consequently, are of different importance to us. The UPA scheme exploits the hierarchical structure of the JPEG2000 coded bitstream in order to assign higher power to the more important parts. In the following, we first evaluate the total distortion of the received image in terms of the bit error probability, and consequently, in terms of the power assigned to different segments of the bitstream. The UPA algorithm then aims at minimizing the expected distortion of the decoded image based on this model.

It is widely assumed that the total distortion of the JPEG2000 decoded bitstream is the summation of the distortions due to each codeblock in the JPEG2000 coded bitstream [6]:

\[
D_{Total} = D_0 + \sum_{i=1}^{N} D_{CB_i} \tag{1}
\]

where \( D_{CB_i} \) is the distortion due to the \( i \)th codeblock (\( CB_i \)) and \( N \) is the number of codeblocks in the bitstream. \( D_0 \) is the inevitable distortion due to quantization in source coding.

The distortion due to each codeblock is a random variable which depends on the coding pass within that codeblock in which the first bit error occurs. Here, we assume that in the error-resilient mode with RESTART/ERTERM enabled, the JPEG2000 decoder can identify the exact coding pass where the first error occurred, and thus discards this and the remaining coding passes of that codeblock. Under this assumption, and using the \( D_{ij} \) evaluated by the “structural information retrieval” block, the expected value of \( D_{CB_i} \) is:

\[
E[D_{CB_i}] = \sum_{j=1}^{N_i} \prod_{k=1}^{j-1} (1 - p_{ik}) \tag{2}
\]

where \( N_i \) is the number of coding passes in \( CB_i \), and \( p_{ij} \) is the probability that there is at least one bit error in \( CP_{ij} \). Therefore:

\[
E[D_{Total}] = D_0 + \sum_{i=1}^{N} \sum_{j=1}^{N_i} p_{ij} D_{ij} \prod_{k=1}^{j-1} (1 - p_{ik}) \tag{3}
\]

Since a bit error at any position within the same coding pass, has the same effect on the resulting image distortion, the UPA algorithm assumes the same amount of power for all bits of a given coding pass, thus, resulting in the same probability of error for all bits within the same coding pass.

Defining \( p_{eb}(i,j) \) as the bit error rate (BER) of \( CP_{ij} \), and \( N_b(i,j) \) as the number of bits in \( CP_{ij} \), \( p_{ij} \) can be written as:

\[
p_{ij} = 1 - (1 - p_{eb}(i,j))^{N_b(i,j)} \tag{4}
\]

Obviously, in the above equation, \( p_{eb}(i,j) \) depends on the power assigned to bits within \( CP_{ij} \), i.e., \( P_{ij} \). Without loss of
Fig. 1. System model

In general, we assume that the symbol period is 1, hence the
transmit power at any given instant is equal to energy of the
signal during any symbol period. For example, for additive
white Gaussian noise (AWGN) channel we have:

\[ p_{eb}(i,j) = Q\left(\sqrt{\frac{2P_{ij}}{N_0}}\right) \]

in which, \(N_0\) is the noise power. As a result, Eq.(3) relates the
expected value of the total distortion of the received image, to
the powers assigned to each coding pass of the bitstream.

The UPA unit aims at minimizing the total distortion at
the receiver, (Eq.(3)), by dividing the total power available to
it unequally among coding passes. This power is shown as
\(P'_{Total}\) in Fig. 1, where:

\[ P'_{Total} = \sum_{i=1}^{N} \sum_{j=1}^{N_i} P_{ij}N_b(i,j) \]

The role of the “power adjustment” unit in calculating \(P'_{Total}\)
is explained in IV.

Minimization of Eq.(3) with the constraint of Eq.(6) is a
non-linear optimization problem. Because the objective func-
tion in Eq.(3) is not a concave function, Gradient-based meth-
ods such as Lagrange multipliers(LM), are not appropriate for
finding the optimum solution of this problem, since they may
find the local optimums instead. Therefore, an optimization
method, which can escape from the local optimums should be
employed here. In this paper, we use the simulated annealing
(SA) method [7]. SA is a generalization of Monte Carlo
method, and is used to locate a good approximation of the
global minimum of an objective function in a large search
space.

IV. IMPLEMENTATION OF THE UPA

As stated in the previous section, the goal is to minimize the
objective function in Eq.(3), by assigning the optimum amount
of power to bits within each coding pass. The dimension of
the search space is determined by the number of coding passes
in the encoded image, which is in turn related to the size of
the coded image, the number of wavelet transform levels, and
the size of the codeblocks. The number of coding passes in
the encoded image can be in the order of a few hundreds and
even higher, resulting in a high computational complexity for
finding the assigned powers.

In order to reduce the time complexity of the algorithm
and to calculate the allocated powers in real time, we pro-
pose to divide the coding passes into several groups and
assign the same power to bits belonging to coding passes
within each group. In order to find a reasonable value for
the number of groups used in the optimization problem, we
solved the problem for the transmission of Lena (512 × 512
and 0.25 bpp) for an AWGN channel, at different channel
signal-to-noise ratios (SNR) and for different group numbers.
The peak-signal-to-noise ratio (PSNR) results are shown in
Fig. 2. As expected, the performance of the system improves
as the number of groups increases. However, performance
improvement becomes negligible for number of groups larger
than 10. Therefore, we choose the number of groups in our
Fig. 3. Effect of the constant parameter $\alpha$ on decoded PSNR curves for transmission of $512 \times 512$ “Lena” image over a fading channel at 0.25 bpp.

Fig. 4. PSNR curves for the transmission of $512 \times 512$ “Lena” image over fading channel at 0.25 bpp with and without CSI, compared to EPA.

optimization problem to be equal to 10.

As per Eq.(5), the bit error probabilities in the objective function of the optimization problem (Eq. (3)), are evaluated assuming an AWGN channel. However, our system is proposed for implementation over wireless fading channels. Thus, the results of the optimization are adjusted at the transmission time, such that the fading factor of the channel is taken into account. After the optimization algorithm calculates the transmission powers for each coding pass, $P_{ij}$, the UPA unit uses the CSI, namely the fading factor $h$, to adjust the final power assigned to each bit of $CP_{ij}$ as follows:

$$P_{ij}' = \frac{P_{ij}}{h^2 + \alpha}$$  \hspace{1cm} (7)

Division by $h^2$ compensates for the effect of fading, however, for practical purposes and to suppress very large powers resulting from very small and near zero fading factors, a constant $\alpha$ is added to the denominator. Practical considerations such as the limitation imposed by the peak power of the amplifier can widely vary based on the application. However, the parameter $\alpha$ can be adjusted to comply with power restrictions.

Although, by adding the constant $\alpha$, the transmission power is confined, on average, $P_{ij}'$ is larger than $P_{ij}$. To take this fact into account, the “power adjustment” unit, adjusts the total power assigned for the transmission of the image ($P_{\text{Total}}$) to the power assigned to the UPA unit, $P_{\text{Total}}'$ as follows:

$$P_{\text{Total}} = P_{\text{Total}}' E\left[\frac{1}{h^2 + \alpha}\right]$$  \hspace{1cm} (8)

where:

$$E\left[\frac{1}{h^2 + \alpha}\right] = \int_{0}^{\infty} \frac{1}{h^2 + \alpha} \frac{h}{\sigma^2} e^{-\frac{h^2}{2\sigma^2}} dh = e^\alpha \int_{0}^{\infty} e^{-\frac{h}{\alpha}} dh$$  \hspace{1cm} (9)

Finally, it should be noted that if CSI is not available at the transmitter, we have to find the optimal power assignments based on the average fading factor of the channel. Therefore, the bit error probabilities, $p_{eb}(i, j)$ in Eq.(4) and subsequently Eq.(3) should be calculated based on the average SNR of the channel [8]:

$$p_{eb}(i, j) = \frac{1}{2}(1 - \sqrt{\gamma_{ij} + 1})$$  \hspace{1cm} (10)

where $\gamma_{ij}$ is the average signal-to-noise ratio of the fading channel corresponding to bit power $P_{ij}$. No further adjustments will be made to the power before transmission.

V. SIMULATION RESULTS

In this section, we investigate the performance of the proposed algorithm for the transmission of JPEG2000 images over wireless channels. In both JPEG2000 encoding and decoding, error-resilient mode is enabled. We have used Kakadu as our JPEG2000 codec with $64 \times 64$ codeblocks, $128 \times 128$ precincts, and five level wavelet decomposition [6]. Images are encoded by enabling the resolution progression option of the JPEG2000 encoder. In all simulations, the header information throughout the bitstream is separated and assumed to be transmitted error free. At the receiver, headers are re-inserted in their original location before JPEG2000 decoding.

The channel is modeled as a point to point wireless channel and is assumed to be Rayleigh flat fading channel for fair comparison with other published papers [1][2][3]. However, our algorithm can be applied to other channel models, e.g. frequency selective channels using OFDM technique. The channel is simulated using Jakes’ model [9]. In this model, the rapidity of channel variations is determined by the “normalized Doppler spread”, $f_D$ (i.e., the Doppler spread normalized by division by the data rate). The noise is assumed to be AWGN with unit variance. Simulations are performed on the standard $512 \times 512$ “Lena” and “Peppers” images with a source coding rate of 0.25 bit per pixel (bpp) to have a fair comparison with the results presented in [1], [2], and [3]. We assume a normalized Doppler spread of $f_D = 10^{-5}$ Hz/bps. The PSNR is used as a measure of the reconstruction quality. We consider two scenarios of with and without CSI, and compare the results.
For the case of a system with CSI, the optimization algorithm is run based on the error probability in AWGN channels. At transmission time, the effect of fading is compensated using Eq.(7). The SA optimization is run four times, each time for 1000 iterations. Out of the four solutions, the answer resulting in minimum distortion based on the distortion model is selected. To show that the result of optimization is not highly sensitive to the value of the constant parameter $\alpha$ in Eq.(7), we evaluated the result of the algorithm for $\alpha = 0.01, 0.05, 0.1$ as shown in Fig. 3. We chose the value of $\alpha = 0.01$ for all our simulations. After finding the transmission powers, the stream is modulated using BPSK and transmitted through the fading channel. The PSNR of the received image is averaged over 200 simulations. The results are presented in Fig. 4. As can be seen from the simulation results, our proposed UPA method provides up to 7dB PSNR improvement for decoded image quality compared to EPA, for PSNR values of around 30 dB.

For the case of no CSI, again we use SA to find the assigned powers but this time based on the error probability of an average fading channel. Therefore, Eq.(10) is used in the evaluation of the objective function. The bit stream is transmitted using BPSK and the calculated power and without any further modifications. These results are also shown in Fig.4. Obviously the image quality in the system with CSI is better than the system without CSI. As can be seen from the results, even in the case of no CSI, the UPA algorithm has a better performance compared to EPA for channel SNRs in the range of 0 to 15 dB.

To show the visual quality of our proposed method, sample decoded images for “Lena” and “Peppers” images (rate 0.25 bpp, $f_D = 10^{-5}$) transmitted using different schemes at SNR=10 dB are shown in Fig. 5. As can be seen from the figures, noticeable visual quality enhancement is achieved by applying UPA to the bitstream.

We have also compared our proposed scheme to the schemes presented in [1], [2] and [3]. These reported results are under channel mismatch conditions, except for SNR=10 dB and show very little improvement in the reconstructed image quality as SNR increases. Unlike the algorithms presented in [1], [2] and [3], which have a high computational complexity, our algorithm is very fast and therefore we can afford to perform the optimization in real-time at each SNR, resulting in a matched channel for all simulations. The results presented in Fig. 6 and Fig. 7 show the superiority of our proposed scheme. In particular, as can be seen from Fig. 6, our system outperforms the method of [3], by up to 4 dB in terms of decoded image PSNR for the transmission of 512×512 “Lena”
image at 0.25 bpp with \( f_D = 10^{-5} \). Our proposed scheme is comparable to the previously published results even at their matched SNR.

VI. CONCLUSION

In this paper, a UPA scheme was proposed for the transmission of JPEG2000 images over flat fading wireless channels. The proposed scheme extracts the contribution of each coding pass within the JPEG2000 coded bitstream in the quality of the decoded image. This is performed in the JPEG2000 error resilient mode with ERTERM/RESTART option enabled.

A distortion model is developed which evaluates the quality of the decoded image based on the powers assigned at coding pass level. According to the contribution of each coding pass in the decoded image quality, the optimization algorithm assigns different transmission powers to bits within each coding pass.

To reduce the complexity of the optimization method, coding passes are grouped together based on their importance and the same power is assigned to coding passes within the same group. When CSI is available, the calculated powers are adjusted at the time of transmission to compensate for the effect of channel fading. When CSI is not available, the optimum power levels are calculated based on the channel signal to noise ratio averaged over the fading factor of the channel.

The proposed scheme was tested for the transmission of “Lena” and “Peppers” images, at 0.25 bpp, over wireless channels. Simulation results confirm the superiority of the UPA method over EPA by up to 7 dB in PSNR. The results of the proposed method were also compared to other state of the art schemes. Under the same channel conditions and bit rate, our proposed method outperforms the results reported in [3] by up to 4 dB in PSNR.

The significance of our proposed method is that more important sections of the image are protected better. By further adjusting the power at the time of transmission based on CSI, we almost entirely remove the effect of fading. It should be noted that while state of the art MAC standards employ rate adjustment algorithms based on the state of the channel, our method can take this rate adjustment into account and further adjust the power to its optimum level.

Finally, the advantage of our proposed scheme is in its low complexity compared to the systems that employ sophisticated error correction codings. Obviously, adding error correction coding to the proposed UPA scheme can further improve the performance of the system.

REFERENCES