Optimal energy distribution in embedded packet video transmission over wireless channels

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Abstract—In this paper the problem of transmitting embedded bitstreams over wireless packet networks is considered. In particular, the authors address the problem of optimal energy allocation in video streams employing fixed-size packets, and analyze the performance under different modulation schemes. Results obtained for the transmission of MPEG-4 FGS bitstreams show the impact of the proposed method in different modulation schemes.

Keywords — error resilience, unequal error protection, power allocation, video transmission, wireless channel, scalable streaming media

I. INTRODUCTION

Wireless packet networks are becoming an interesting infrastructure for the implementation of both traditional and innovative applications. Under this perspective, video delivery over wireless network is considered an important issue, and several problems related to the channel characteristics, such as the relatively high percentage of transmission errors and the limited energy of portable devices, must be addressed.

In this paper, we take advantage of the structure of embedded bitstreams for implementing packet prioritization based on non-uniform allocation of the available transmission energy. Embedded bitstreams are used in various multimedia coding algorithms. In video coding, it is possible to find this approach in the MPEG-4 [1] implementation of Fine Granularity Scalability (FGS) [2]. In MPEG-4 FGS, video data are divided into two bitstreams: Base Layer (BL) and Enhancement Layer (EL). While BL is a low resolution coded version of the video, the EL progressively adds information to the BL in order to obtain more detailed versions of the data. The EL is bit-plane encoded and therefore it can be treated as an embedded bitstream. In the EL, data are encoded in such a way that, in the case the bitstream is truncated, a lower resolution of the original video can still be decoded. As a result, the data in the bitstream have different levels of importance and a higher level of protection can be given to the more significant bit-planes, allowing lower protection as the bit-planes become less significant [3].

In the proposed paper, based on previous work in [4], optimal energy distribution is used to perform non-uniform error protection in different modulation schemes.

The structure of the paper is the following: section II presents a description of the proposed approach, while section III provides an analysis of the performance of the method using different digital modulation techniques. Finally, section IV gives some conclusions and outlines about future work on the topic.

II. DESCRIPTION OF THE PROPOSED APPROACH

Assuming that the BL is always received correctly and that a maximum amount of energy \( E_{\text{tot}} \) per EL of each frame is given, our goal is to determine how to allocate the available energy in such a way that minimizes the overall distortion.

If we partition the EL bitstream into \( L \) packets and transmit these packets over the channel, the minimization problem can be expressed as:

\[
\min_{E_b} \{ D_{\text{BL}} - E[\Delta_{\text{EL}}] \} \text{ s.t. } E_{\text{tot}} = \sum_{l=1}^{L} B_l \cdot E_b^l
\]

(1)

where \( D_{\text{BL}} \) is the distortion of the BL, \( E[\Delta_{\text{EL}}] \) is the expected value of the distortion improvement introduced by jointly decoding the BL and all the correctly received EL packets, \( E_{\text{tot}} \) is the energy budget for the EL for the current frame, \( B_l \) is the number of bits of the \( l \)-th packet, and \( E_b^l \) is the energy used for transmitting each bit of the packet \( l \).

We assume that each packet can be employed in the decoding stage only if itself and all the previous EL packets are correctly received. The expected distortion improvement can then be written as:

\[
E[\Delta_{\text{EL}}] = \sum_{l=1}^{L} \prod_{i=1}^{l} (1 - p_i) \cdot \Delta_i, \quad (2)
\]

where \( p_i \) is the loss probability for the \( l \)-th packet, and \( \Delta_i \) is the distortion improvement introduced by it.

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We can solve the minimization problem by introducing a Lagrange multiplier $\lambda$, and solving the following unconstrained problem:

$$\min_{E_b} J = \min_{E_b} \left\{ D_{E_b} - \sum_{j=1}^{L} \prod_{i=1}^{j} (1 - \rho_i) \cdot \Delta_l + \lambda \left( \sum_{j=1}^{L} B_j \cdot E_b^j \right) \right\}.$$  \hspace{1cm} (3)

Since the average transmission energy used by the adopted modulation scheme directly affects the probability of packet loss, we can assume that the relationship between the probability of loss for the $l$-th packet $\rho_l$, and the energy $E_b^l$ used for transmitting it is known at the transmitter:

$$\rho_l = g(E_b^l).$$  \hspace{1cm} (4)

where the function $g$ can be defined using an analytical model of the wireless channel.

We can observe that, at the optimal solution, the first derivative of the cost function $J$ with respect to $E_b^j$, for $j = 1, \ldots, L$ is equal to zero. We can then write the following expression:

$$\frac{\partial J}{\partial E_b^j} = \frac{\partial E_b^j}{\partial E_b^j} \cdot (1 - \rho_j)^{-1} \cdot \sum_{i=1}^{j} \prod_{j=1}^{i} (1 - \rho_i) \cdot \Delta_l + \lambda \cdot B_j = 0.$$  \hspace{1cm} (5)

With some simple manipulations, we can obtain from (5) the relationship, valid for packets $1, \ldots, L-1$, that formalizes the dependency of the transmission bit energy of the $j$-th packet from the bit energy of the following packets, $(j+1)$ to $L$:

$$\left( \frac{\partial E_b^j}{\partial E_b^j} \right)^{-1} \cdot (1 - \rho_j) \cdot B_j = \left( \frac{\partial E_b^{j+1}}{\partial E_b^{j+1}} \right)^{-1} \cdot \left( \sum_{i=1}^{j} \prod_{i=1}^{j} (1 - \rho_i) \cdot \Delta_l^{-1} \right) + 1.$$  \hspace{1cm} (6)

The probability of packet loss can be written as the probability of losing at least one bit:

$$\rho_j = 1 - (1 - \varepsilon)^{\rho_j},$$  \hspace{1cm} (7)

where $\varepsilon$ is the bit error probability, and depends on the adopted modulation scheme.

In the case of the BPSK modulation, $\varepsilon$ is given by [5]:

$$\varepsilon = G(\sqrt{2 \cdot \gamma_b}), \quad \text{with} \quad \gamma_b = \frac{E_b}{N_b}.$$  \hspace{1cm} (8)

$E_b$ is the bit energy, $N_b$ is the noise power per Hz, and the function $G(x)$ is given by the well-known formula:

$$G(x) = \int \frac{1}{\sqrt{2\pi}} e^{-x^2/2} du.$$  \hspace{1cm} (9)

Generalizing, the bit error probability can be written as:

$$\varepsilon = a \cdot G(\sqrt{a \cdot \gamma_b}).$$  \hspace{1cm} (10)

The values of $a$ and $\alpha$ for different modulations are summarized in Table 1.

| TABLE I. PARAMETERS $a, \alpha$, AND THE SPECTRAL EFFICIENCY $r_b/B_s$ FOR DIFFERENT MODULATIONS |
|----------------|----------------|
| Modulation     | $a$ | $\alpha$ | $r_b/B_s$ |
| FSK            | 1   | 1        | 1         |
| BPSK; PSK      | 1   | 2        | 1         |
| MSK; QAM; QPSK | 1   | 2        | 2         |
| DPSK (M24)     | 2K  | 4K       | 2         |

Equation (6) can then be expressed as:

$$1 - a \cdot G(\frac{a \cdot E_b}{\sqrt{N_b}}) \cdot E_b^{1/2} =$$

$$1 - a \cdot G(\frac{a \cdot E_b}{\sqrt{N_b}}) \cdot E_b^{1/2}.$$  \hspace{1cm} (11)

The minimization problem can be solved by finding the value of $E_b^j$ that satisfies the energy constraint. Since the closed form solution to the problem is difficult to compute analytically, a numerical method is used.

Indeed, (11) allows one to compute the energy assigned to packet $j$, $E_b^j$, from the one assigned to the subsequent packets $\{E_b^{j+1}, \ldots, E_b^L\}$. Starting from a given $E_b^L$, we can then compute the energy distribution $\{E_b^{j+1}, \ldots, E_b^L\}$ and hence obtain, for a specific value of $E_b^L$, the energy budget required for transmitting the packets in an optimal way. We can use (11) to construct a curve $E_{\text{budget}}(E_b^L)$ and numerically find (e.g. using the bisection method) the value of $E_b^L$ that satisfies the energy constraint, obtaining in this way the optimal energy distribution among the packets. When a solution with $E_b^L$ greater than zero does not exist, the solution of the minimization problem must be searched using $L-1$ packets.
Once the energy levels for each packet are known, the transmission power for packet \( j \) can be calculated using the following relationship:

\[
P_j = E_j \cdot R.
\]

(12)

III. PERFORMANCE ANALYSIS

The presented results are achieved through numerical simulations on the QCIF test sequence "foreman," with a frame rate of 10 fps. Noise power \( N_0 \) is set to \( 10^{-4} \) W/Hz. The sequence is encoded with the MPEG-4 FGS algorithm [6], setting a fixed bitrate of 14Kbps for the BL. The number of transmitted EL packets is calculated based on the video frame rate and the available bit rate \( r_s \). The value of \( r_s \) depends on the transmission bandwidth \( B_T \) and the spectral efficiency of the adopted modulation scheme (Table 1), according to the equation:

\[
E_s = \frac{r_s}{B_T} \left[ \frac{\text{bps}}{\text{Hz}} \right].
\]

(13)

The optimal energy allocation strategy is in fact found through numerical resolution of the set of eqs. represented by (11) – see section II for details.

Fig. 1 summarizes the achieved results for the transmission of sequence using different modulation schemes (BPSK, MSK, PSK): packet size is fixed and equal to 100 bytes; maximum energy \( E_{max} \) is set to 0.5 Joules; and the transmission bandwidth \( B_T \) is set to 100 KHz. The employed performance metric is the peak signal-to-noise ratio (PSNR) at the video decoder, as usual in video transmission schemes. Fig. 1 also presents the PSNR level in the case of BL only and when both BL and EL are correctly received.

Analysis of the achieved PSNR demonstrates the advantage of the proposed method against equal energy distribution among all EL packets. Average PSNR gain can be up to 2 dB, depending on the energy budget and the modulation scheme, as shown in Fig. 2.

Figure 2 also shows how, for limited energy budgets, the optimized scheme outperforms the equal distribution method while, as the budget increases, the gain progressively vanishes. Indeed, high values of PSNR gain are in general due to the fact that the available energy is too small for protecting all the packets in an acceptable way. For this reason, the proposed method does not transmit some of the less important layers, thus reserving all the resources for the more important packets. The equal distribution method splits the energy among all the packets, which receive a very weak protection when the energy budget is reduced.

From Fig. 1 and 2 some interesting observations can be made regarding the different behavior of the method with different modulations.

FSK is less efficient in protecting data bits than PSK, but with optimal energy distribution, the PSNR gain at the receiver diminishes with respect to the equal distribution.

MSK has a higher spectral efficiency than other schemes such as FSK and BPSK. This because MSK can encode more than one bit per symbol, and succeeds in this way in transmitting at higher bitrates using the same bandwidth. When transmitting video, this means being able to transmit more information related to each frame, thus allowing, if the data is correctly received, a better reconstruction of the original video sequence. In our case, this is achieved by transmitting more bits from the EL. As a drawback, MSK needs more power for achieving this bitrate and maintaining the same bit protection as BPSK. This means that, if the energy budget per frame is fixed, the bitstream is more susceptible to transmission errors. As a consequence, when the energy budget is low, the advantage of transmitting at a higher bitrate is vanishes by the fact that the resources are not enough for transmitting all the packets allowed by the bit budget in an acceptable way. In this case, when using the equal energy distribution scheme, the PSNR is much lower than it would be if all the packets were received and when using the optimal distribution, the attained performance equals the one obtained with BPSK (Fig. 1).

IV. CONCLUSIONS AND FUTURE WORK

In conclusion, a method for optimal energy allocation in packet video transmission over wireless channels was presented and tested for different digital modulation schemes. Future work will deal with the introduction of forward error correction codes in our model, in order to allow extensive frame-level analysis of modern wireless transport networks.

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Figure 1. PSNR comparison of the equal energy distribution method and the proposed scheme for different modulations. Optimal BPSK and MSK achieve same results, while equal energy FSK and MSK achieve results near the BL PSNR (Cot = 0.5 Joule, BT = 100 KHz).

Figure 2. Average PSNR comparison of equal energy distribution method and the proposed scheme for different modulations and energy budgets (BT = 100 KHz).