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Research Article

A Study on the Usage of Cross-Layer Power Control and Forward Error Correction for Embedded Video Transmission over Wireless Links

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Cross-layering is a design paradigm for overcoming the limitations deriving from the ISO/OSI layering principle, thus improving the performance of communications in specific scenarios, such as wireless multimedia communications. However, most available solutions are based on empirical considerations, and do not provide a theoretical background supporting such approaches. The paper aims at providing an analytical framework for the study of single-hop video delivery over a wireless link, enabling cross-layer interactions for performance optimization using power control and FEC and providing a useful tool to determine the potential gain deriving from the employment of such design paradigm. The analysis is performed using rate-distortion information of an embedded video bitstream jointly with a Lagrangian power minimization approach. Simulation results underline that cross-layering can provide relevant improvement in specific environments and that the proposed approach is able to capitalize on the advantage deriving from its deployment.

1. INTRODUCTION

With the worldwide diffusion of wireless networks (WLANs, 3G cellular networks), the usage of wireless links for delivery of video streams is becoming a common practice. However, unlike wired links, wireless connections suffer from a number of specific drawbacks, including time-varying behavior, limited shared bandwidth, noisy medium, and user mobility. Moreover, the mobility of the user terminals implies the usage of batteries, and thus the need to limit transmission power and carefully utilize energy in order to maximize device lifetime. This aspect is also being considered by well-known and worldwide diffused standards like IEEE 802.11, which recently activated working group IEEE 802.11 h [1] in order to address the aspect of power saving.

In this scenario, optimized video transmission involves at least joint control of source coding parameters (encoded stream packetization, packet classification), medium access control procedures (ARQ, forward error correction), and physical parameters (transmission power, channel sensing). As a consequence, effective optimization can be achieved only by means of cross-layering solutions.

Indeed, cross-layering [2] is a well-known design principle which was recently proposed to overcome some limitations deriving from the standardized layering paradigm (such as OSI/OSI reference model) imposing independent design of protocols at different layers and standardized (and limited) interactions among adjacent layers. At this point, it is useful to mention that the authors share most of the cautionary perspective on cross-layering illustrated in [3], and—as it will be clearly discussed in the remainder of the paper—mainly aim at providing an analytical framework for evaluating the scenarios and the potential benefits deriving from the application of such a design principle.

The paper considers application of cross-layering paradigm to support unequal error protection (UEP) of video streams. UEP strategies for transmission of progressively coded images and videos have been implemented in various fashions, as some techniques designed for other contexts have been adapted to the transmission of embedded

bitstreams. Data is implicitly sorted by its importance, and this feature can be directly used for the implementation of error resilience techniques based on UEP. Traditional equal error protection (EEP) schemes consider all the data as having the same importance and assign the same degree of protection to the whole bitstream. On the other hand, UEP schemes give more importance, hence more protection, to the most critical parts of the coded image.

Unequal error protection techniques have been studied in the past [4] for differentiating protection between different layers in traditional layered scalable coding. These methods, based on techniques such as automatic repeat request (ARQ) and forward error correction (FEC), can be adapted to the transmission of embedded bitstreams. Reed-Solomon codes were used by Natu and Taubman [5] for the protection of JPEG2000 bitstreams during transmission over wireless channels. In [6], channel coding is used for implementing UEP of a JPEG2000 bitstream.

For video transmission, the application of UEP within a fine-grained scalable (FGS) bitstream was first considered by van der Schaar and Radha in [7], where the frame-grained loss protection (FGLP) framework was introduced. Based on it, Yang et al. [8] proposed a "degressive" protection algorithm (DEP) based on FEC for optimal assignment of protection redundancy among bit-planes. In [9], Wang et al. studied the problem of rate-distortion optimized UEP for progressive FGS (PFGS) over wireless channels using prioritized FEC for the base layer and enhancement layer. A similar problem was studied in [10], where the objective was to minimize the processing power for PFGS video given bandwidth and distortion constraints. In [11], a joint FEC and transmission power allocation scheme for layered video transmission over a multiple user CDMA networks was proposed. In that work, scalability was achieved using 3D SPIHT (wavelet based coding). The objective was to minimize the end-to-end distortion through optimal bit allocation among source layers and power allocation among different CDMA channels. The authors in [12] considered jointly adapting the source bit rate and the transmission power in order to maximize the performance of a CDMA system subject to a constraint on the equivalent bandwidth. In that work, an H.263+ codec was used to generate the layered bitstream. Relevant works on cross-layering between application and physical layers are provided by [13], where maximization of end-to-end quality of service is studied by enabling adaptive modulation and coding, and [14], where H.264/AVC video is protected by using turbo codes.

Recent works on the topic of optimization of video delivery over wireless channels are focused on the usage of embedded video streams (3D-ESCOT) [15, 16], and considered physical layer protocols are those employed in existing/next generation wireless networks (CDMA and OFDM). In [17], UEP, retransmissions, and interleaving are employed to reduce quality fluctuations in video quality of streaming scalable video, while in [18], motion-compensated temporal filtering (MCTF) scalable video coding (SVC) is supported by two-dimensional channel coding to improve resilience to channel errors. Preliminary works are also available, related to the problem of video transport over IP networks, like in [19], where UEP of video packets is proposed driven by a rate-distortion optimization principle.

However, a few works are available on video quality optimization using power control and FEC, such as [20], where joint coding-power control is employed for optimization of video delivery over CDMA cellular network, [21], where power control and channel coding are jointly employed to improve performance over wireless channels, and [22], where the authors introduced the application of cross-layer optimization between physical/link-layer functionalities (power, FEC) and application stream characteristics (embedded video stream).

In this paper, we analyze the problem of optimized video transmission over an uplink wireless channel, considering an architecture which enables to control forward error correction and transmission power on the basis of channel status and source information. Basically, the problem of providing the best possible quality is formulated and solved in order to derive useful guidelines on the effective benefits and usage scenarios of cross-layering. The reference coding algorithm will be MPEG-4 FGS [23], but the process can be applied to other embedded bitstreams as well. However, one of the main innovation points of the paper is the analysis of the potential benefits deriving from the implementation of cross-layering against standard "layered" approach.

In order to provide a virtual positioning of the work within the existing state-of-the-art, Table 1 classifies some of the relevant works presented above in terms of some relevant features. More in details, for each considered paper, the table illustrates whether it is based on scalable video, FEC, power control, ARQ (retransmission), rate-distortion model, and so forth. Only more relevant schemes are considered for sake of clarity.

More in details, the novel contributions of the paper can be outlined as follows:

(1) the definition of a suitable framework and an architecture for evaluating the potential benefits of cross-layer design in embedded video transmission over a wireless link under energy constraints,

(2) the analysis of the advantages and drawbacks deriving from cross-layer design rather than maintaining codec/link-layer independence in video transmission over wireless links,

(3) the flexibility of the proposed framework in terms of adaptability to different scenarios (i.e., different modulations, channel models, codec configurations),

(4) the usage of the rate-distortion characteristics of the embedded video bitstream, enabling to generalize the results to more than a specific video sequence (or codec).

The paper is organized as follows. Section 2 introduces the considered scenario and describes a possible architecture for enabling cross-layer interaction. Section 3 provides insight to the characterization of an embedded video stream, focusing on MPEG-4 FGS mode. Section 4 presents the statement of the problem and proposes an analytical method to

Table 1: Comparison among relevant state-of-the-art approaches and the work presented in the paper.

	Rate-distortion model	Video stream scalability	Power control	FEC	ARQ
Reference [8]	×	FGS	×	✓	×
Reference [9]	✓	FGS	×	✓	×
Reference [11]	×	Layered	✓	✓	×
Reference [17]	×	Multiple description	×	✓	✓
References [13, 18]	×	SVC/Layered	×	✓	×
Reference [19]	✓	Adaptive slicing	×	✓	×
Reference [14]	×	H.264/AVC	×	✓	×
Reference [20]	×	JSCC	✓	✓	×
Reference [21]	×	Layered	✓	✓	×
Proposed	✓	Embedded (MPEG-4 FGS for testing)	✓	✓	×

provide a numerical solution. Results are presented and analyzed in Section 5, while Section 6 draws conclusions and provides insights on future works on the topic.

2. THE CONSIDERED SCENARIO AND REFERENCE ARCHITECTURE

The considered scenario is a wireless video sensor network, where mobile devices equipped with video sensors (e.g., PDAs, smart phones) are moving within an area covered by wireless cells. Each mobile terminal within a wireless cell needs to transmit a video sequence to a remote control center or video server located on the Internet (see Figure 1). Mobility of the terminals implies the usage of batteries and thus constraints on power consumption in order to maximize the lifetime of the device.

We are interested in studying the optimal set of parameters able to provide satisfactory video quality and proper energy savings within the single-hop uplink transmission between the mobile node and the wireless access point. As mentioned in Section 1, power control and forward error correction are considered.

In order to provide the required functionality, an additional power control module needs to be implemented within the wireless interface of the mobile terminal, which controls the power allocated to each video packet on the basis of information provided by the MPEG-4 video encoder and radio MAC/physical modules.

Signal-to-noise ratio (SNR) information is required for effective power control since it provides an estimate of the status of the channel. Several works, like [24, 25], discussed how to properly estimate SNR on a wireless link, for example on an IEEE 802.11 link. A common assumption is to consider the link symmetric, implying that SNR observed from either station on the link is very similar, and thus allowing to use the SNR of the last ACK frame as an indication of the SNR at the other side [25]. Therefore, in the following paragraphs we will assume that SNR information can be directly calculated at the MAC level.

The resulting cross-layering reference architecture is presented in Figure 2, where the power control module drives

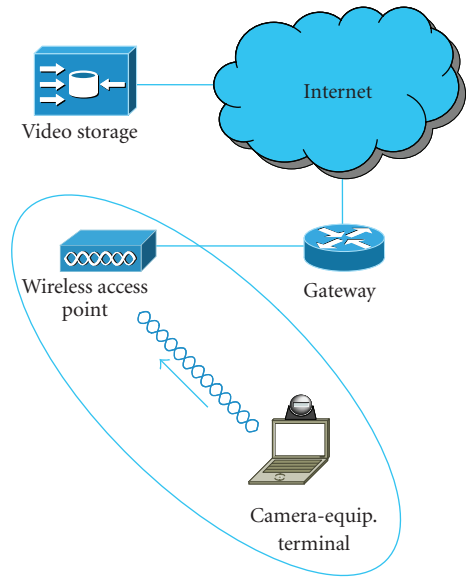

Figure 1: The scenario under consideration.

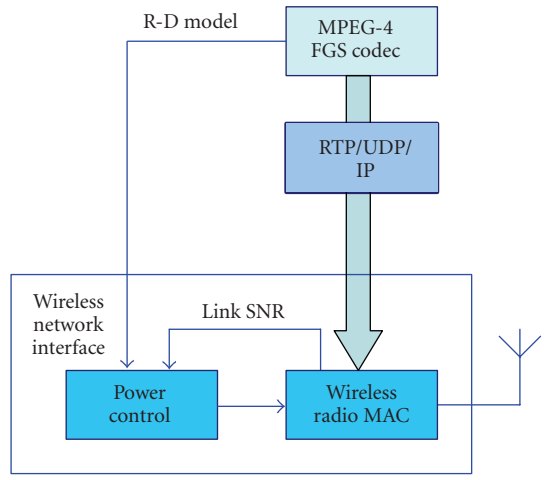

Figure 2: Block diagram of the main components at the mobile terminal side.

the power per frame allocated by the radio interface on the basis of the link state (Link SNR) and information related to the visual importance of each video packet in the form of rate-distortion characteristic of the compressed video (R-D model). In Figure 2, the wireless network interface represents the whole network adapter of the device, thus comprising the physical as well as the link layers—as often encountered in real implementations.

In the remainder of the paper, the encapsulation of video data by RTP, UDP, and IP protocols is not considered, since the modeling and analysis are oriented towards the MAC and physical level only. Furthermore, no fragmentation of the video packets produced by MPEG-4 FGS encoder is allowed at lower levels.

3. CHARACTERIZATION OF THE EMBEDDED VIDEO STREAM

3.1. *Characteristics and model of a progressively coded bitstream*

Multimedia data can be coded with progressive coding techniques. When decoded, the generated bitstreams progressively add enhancement information to the recovered data. The decoding process can be interrupted at any point, and the data decoded up to that point can be interpreted as a low-resolution or low-quality version of the fully decoded data. In progressively coded bitstreams, there are no distinct layers, as with traditional layered coding. Indeed, with the traditional approach, scalability is achieved by coding the data in different separate coding layers, starting with the *base layer* (BL), which contains basic information, and then generating one or more *enhancement layers* (ELs). For decoding, the BL is needed before the first EL can be decoded and so on. In progressive coding, scalability is achieved though direct truncation of the bitstream. This approach differs from traditional layered methods for video scalability because of its capability to achieve a smooth transition between different bit rates.

In the context of rate control, progressively coded bitstreams can be used for obtaining fine granularity data representations at lower bit rates, since such bitstreams have the property of allowing different spatial/quality resolutions depending on the amount of data being transmitted and decoded.

The most popular progressive coding implementations are based on wavelet transforms and/or bit-plane coding. These techniques enable the progressive coding of images, video, and even audio data. For example, for image coding, wavelet-based coding techniques, like those used in SPHIT [26] and EBCOT [27], can be used. These techniques differ on how the compression is achieved, but all of them can generate progressively coded bitstreams. In particular, wavelet transform is used by the newest image compression standard, JPEG2000 [28, 29], which is based on the EBCOT paradigm. JPEG2000 not only delivers a state-of-the-art compression performance, but is also flexible to accommodate tools for the implementation of region of interest (RoI) coding, perception-based quality optimization, and quality layers.

Wavelets can be further used in video compression. For example, 3D wavelet coding schemes, such as 3D SPHIT [30], can be used in obtaining embedded bitstreams of video data. These techniques group together a sequence of frames and apply the 3D wavelet transform to them, eventually allowing both temporal and quality scalabilities.

Another important approach is represented by the fine granular scalability (FGS), as included in the streaming profile of the MPEG-4 standard [23, 31], that uses a mixed implementation of layered scalability and bit-plane coding for obtaining two layers, a BL with essential information about the sequence, and a progressively coded EL that adds information and detail to the BL.

Due to its structure, the EL can be truncated at any point and still be used to add information to the decoded BL. The inherent scalability and flexibility of FGS enable complexity scalability and easy resource adaptation depending on the capabilities of video devices. Thus, FGS is suitable for video conferencing and video multicasting. An interesting overview of applications enabled by FGS technology is given in [32].

Due to the many applications of the various forms of scalability, the joint video team (JVT) composed by ITU-T and ISO/IEC experts groups is currently working towards a scalable extension of the H.264/MPEG4-AVC [33]. The current reference model, commonly known as scalable video coding (SVC), includes both fine grain SNR (quality) scalability (FGS) and coarse grain SNR (CGS) scalability modes. SVC has obtained the important result of successfully addressing the problem of coding efficiency reduction, a typical issue of previous scalability schemes such as MPEG-4. Even if scalable codes have been heavily criticized in the past for such reason, the advent of SVC gives to scalable coding a new perspective, and it is not unreasonable to expect an increase of efficiency from future developments.

For the purpose of our discussion, we consider a generic embedded coded bitstream with a set of truncation points. We separately consider the data added between a given truncation point and the subsequent truncation point, and define in this way different coding layers. Embedded bitstreams are constructed in such a way that data in one point of the bitstream is strictly dependent on preceding data. As a consequence, the incorrect reception of one layer (preceding data) affects the decoding of all the information added by the subsequent ones.

For sake of simplicity, we assume that layer zero or base layer (see Section 3.2), which contains the most important information (such as header information for images or basic frame information for video), together with a small amount of data, is always received correctly. This can be possibly achieved by strong protection of such layer, for example, implementing an automatic repeat request (ARQ) scheme, or by transmitting BL data during the negotiation phase at the beginning of a video transmission transaction.

Under this hypothesis, we can compute the average distortion in the reconstructed data by considering the contributions of each single layer. If we consider an additive distortion metric, such as the mean-squared error (MSE), the

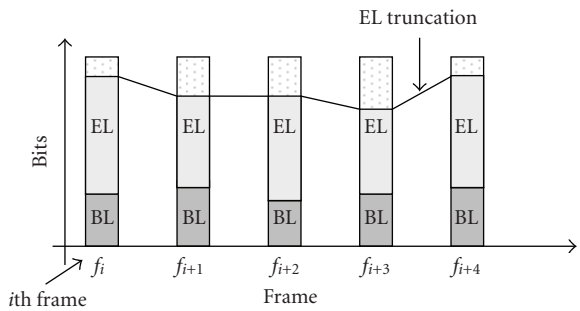

Figure 3: Example of rate control applied to FGS bitstream.

distortion associated with the reconstructed data can be expressed as follows:

$$D = D_0 - E[\Delta] = D_0 - \sum_{l=1}^{L} \prod_{i=1}^{l} (1 - \rho_i) \cdot \Delta_l, \qquad (1)$$

where D_0 is the distortion incurred if only layer zero is received, $E[\Delta]$ is the mean distortion reduction due to the reception of L layers, ρ_l is the probability of loss for the lth layer, and Δ_l is the distortion reduction due to the reception of the lth layer.

From (1), we notice that lower-numbered layers have greater importance than higher ones, thus the transmission of each layer critically depends on its position in the bitstream. Stronger protection of the lower layers becomes therefore essential, and as a natural consequence it is straightforward to combine this multilayered approach with a UEP scheme for achieving improved quality of the received video.

3.2. Progressive scalability in MPEG4

In MPEG-4 FGS, the BL behaves as a standard baseline MPEG-4 compressed bitstream, while the EL is obtained by encoding the difference between the BL and the original sequence. Fine granular scalability is provided by the EL, since residual data is block-encoded and the DCT coefficients are bit-plane coded, thus generating an embedded bitstream. Since the EL encoded data is transmitted starting from the most significant bit-plane (MSBP) to the least significant bit-plane (LSBP), a truncated EL bitstream (Figure 3) can still be used for improving, together with the BL, the reconstruction quality of the video sequence.

If the individual bit-planes are considered, the contribution given to the quality of the decoded sequence by the data encoded in the EL bitstream decreases as we move from the most significant bit-plane (MSBP) to the least significant one (LSBP). At the same time, data from MSBP is easier to compress, since it is more correlated than data from the LSBP. This aspect is shown in the characteristic rate-distortion (R-D) curve (Figure 5). Typically, the most significant bit-plane (BP1) is the smallest in size (i.e., it requires the smallest number of bits), and bit-plane size significantly increases from the most significant to the least significant bit-plane. In Figure 4, the average size of the different bit-planes

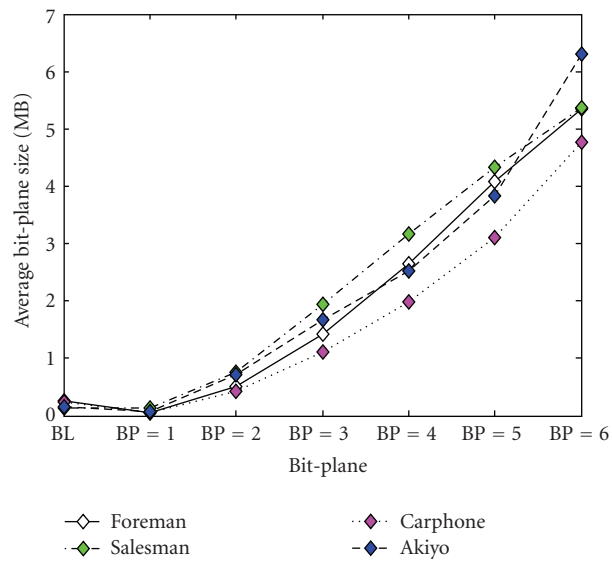

Figure 4: Average size of the bit-planes for the various QCIF reference sequences.

is plot for various reference sequences (BL is encoded with a bit rate of 14 Kbps). More details on the R-D curve are given in Section 3.3.

By taking advantage of the structure of MPEG-4 FGS coding, we can implement a prioritized UEP scheme for the EL packet [7]. This approach is possible mainly for two reasons. First, it is not possible to decode the data of a bit-plane without decoding the preceding bit-planes. Second, the data of the MSBP also carries more (perceptually relevant) information with respect to the LSBP.

The highest level of protection can be given to the MSBP, gradually reducing the protection as the bit-planes become (perceptually) less significant. This coding approach can simplify rate control algorithms implementation and can be used in combination with unequal error protection policies [7, 34].

3.3. Rate-distortion model of the FGS bitstream

Working with an operational rate-distortion (ORD) model, that is, measuring the distortion for each packet, is typically a computationally intensive task. A workaround to this problem is to use a rate-distortion (R-D) model of the EL based on the statistics collected during the encoding phase. The rate-distortion model can be derived either from empirical considerations or from analytical calculations. An interesting analysis of the FGS EL layer is given by Loguinov and Radha in [35], where also a distortion model is defined.

In this work, we utilize experimental measurements to construct an R-D curve. Based on them, the R-D model is built using a piecewise linear curve (linear within each bit-plane) [36, 37]. This is reasonable if we assume the statistical properties uniform within a single bit-plane and consider the fact that inside a bit-plane the distortion improves gradually by adding bit-plane information one MB at a time. R-D

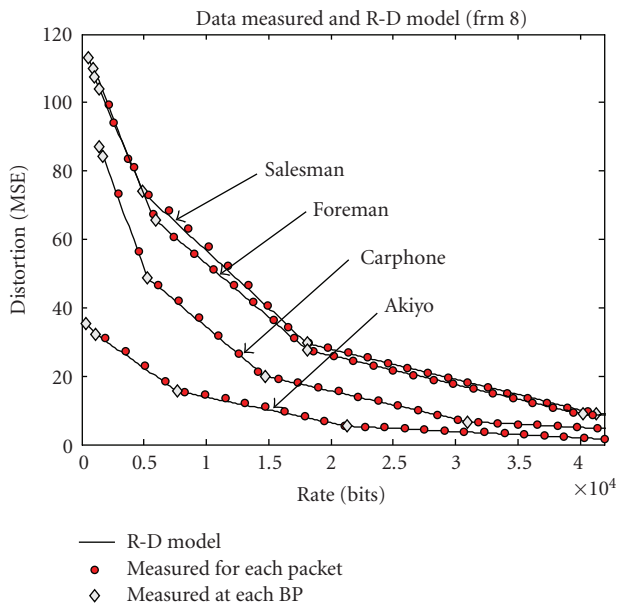

Figure 5: Comparison between the measured data and the R-D curve calculated from the BP data.

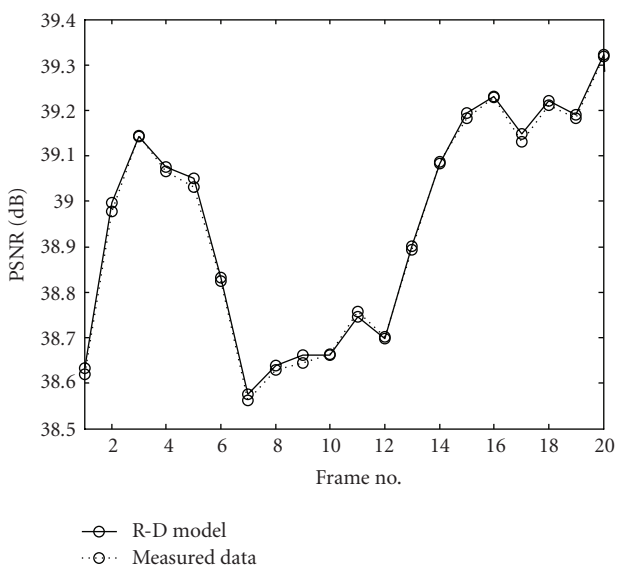

Figure 6: Comparison between the PSNR obtained using measured data and the R-D model.

data measured for each BP is shown in Figure 5 for different video sequences. As it can be seen, they validate quite well the linear-within-a-bit-plane model. The actual R-D data and the linear R-D model are both utilized by the energy allocation algorithm, to be described later, resulting in the reconstructed video of the quality shown in Figure 6. As it can be observed, the quality resulting from the two R-D models is almost indistinguishable. It is worthwhile to be mentioned here that the R-D data can be easily calculated also in the frequency domain, as highlighted in [38].

4. MODELING AND ANALYZING THE PROBLEM

4.1. The general framework

For simplicity, we consider transmitting each layer in a single link-layer packet. This assumption is not limiting, as it is possible to consider layer fragmentation in multiple link-layer packets just evaluating the distortion contribution of each portion of data in a way similar to the one described in Section 3.3. Since the design objective is to limit the energy consumption within a predetermined budget, we assume that the transmission power can be controlled at packet level. Unequal error protection can then be achieved by adjusting the transmission power used by each packet.

Link-layer retransmissions, which are a common strategy to improve reliability of communication on wireless links, are not considered, mainly for two reasons.

(1) Retransmissions introduce additional delay in data delivery, which is not controllable. As a consequence, delayed packets could be received "too late" and therefore become unusable, thus introducing serious power waste.

(2) The cost for retransmitting a packet multiplies the power consumption related to each packet. Since the goal is to minimize power consumption (or maximize battery lifetime), a single packet retransmission would double power consumption, while a lower increase in the transmission power could bring more benefits in terms of probability of correct reception.

Based on the hypothesis described above, the problem of transmitting a bitstream of compressed multimedia data with minimum end-to-end distortion D, given a limited energy budget, can be formulated as follows:

$$\min_{P_l} D, \text{ s.t. } E_{\text{tot}} = \sum_{l=1}^{L} \frac{B_l \cdot P_l}{R}, \tag{2}$$

where R is the channel rate, L the total number of transmitted packets (or layers), B_l and P_l are the size in bits and the power assigned to the lth packet, respectively, and E_{tot} the available total energy. The number of packets L is related to the bit budget. Indeed, given a bit rate R and the desired maximum transmission time T, the bit budget must equal $T \cdot R$. In case of equal size packets, L is given by $T \cdot R$ divided by the packet size B_l.

The problem can be solved using the Lagrangian relaxation method. By introducing the Lagrange multiplier, λ, (2) can be converted into the following unconstrained problem:

$$\min_{P_l} J = \min_{P_l} \left\{ D_0 - \sum_{l=1}^{L} \prod_{i=1}^{l} (1-\rho_i) \cdot \Delta_l + \lambda \left(\sum_{l=1}^{L} \frac{B_l \cdot P_l}{R} - E_{\text{tot}} \right) \right\}, \tag{3}$$

where J is the resulting cost function.

Since the average transmission power used by a modulation scheme directly affects the probability of packet loss, we can represent the relationship between the loss probability ρ_l of the lth packet and the transmission power P_l with a function g, such that $\rho_l = g(P_l)$. We assume that such relationship is known at the transmitter, defined using an analytical model of the wireless channel or through actual measurements.

The necessary condition for an optimum point of the cost function J is that its first derivative with respect to P_j, with $j = 1, \ldots, L$, is null. The first derivative of the cost function J with respect to P_L can be written as

$$\frac{\partial J}{\partial P_L} = \frac{\partial \rho_L}{\partial P_L} \cdot \prod_{i=1}^{L-1} (1-\rho_i) \cdot \Delta_L + \lambda \frac{B_L}{R}. \tag{4}$$

Setting it equal to zero and rearranging terms, it is possible to derive the following expressions, for $\rho_i \neq 1$:

$$\prod_{i=1}^{L-1} (1-\rho_i) = \lambda \cdot f(P_L, B_L, \Delta_L), \tag{5}$$

where

$$f(P_L, B_L, \Delta_L) = -\frac{B_L}{R \cdot \Delta_L} \cdot \left(\frac{\partial \rho_L}{\partial P_L}\right)^{-1}. \tag{6}$$

From (5), we can obtain the expression

$$\prod_{i=1}^{j} (1-\rho_i) = \lambda \cdot f(P_L, B_L, \Delta_L) \cdot \prod_{h=j+1}^{L-1} (1-\rho_h)^{-1}, \quad \text{for } j = 1, \ldots, L-2. \tag{7}$$

The first derivative of the cost function J with respect to P_j can be written, for $\rho_j \neq 1$ and $i < L$, as

$$\frac{\partial J}{\partial P_j} = \frac{\partial \rho_j}{\partial P_j} \cdot (1-\rho_j)^{-1} \cdot \sum_{l=j}^{L} \left(\prod_{i=1}^{l} (1-\rho_i) \right) \cdot \Delta_l + \lambda \frac{B_j}{R} = 0. \tag{8}$$

Substituting expressions (7) into (8), we obtain, for $j < L$,

$$\begin{aligned} \frac{\partial J}{\partial P_j} = & \frac{\partial \rho_j}{\partial P_j} \\ & \cdot (1-\rho_j)^{-1} \cdot \left[\sum_{l=j}^{L-1} \left[\lambda \cdot f(P_L, B_L, \Delta_L) \cdot \prod_{h=j+1}^{L-1} (1-\rho_h)^{-1} \right] \right. \\ & \left. \cdot \Delta_l + \lambda \cdot (1-\rho_L) \cdot f(P_L) \cdot \Delta_L \right] \\ & + \lambda \cdot \frac{B_j}{R} = 0, \end{aligned} \tag{9}$$

or

$$\begin{aligned} \frac{\partial J}{\partial P_j} = \lambda \cdot \Bigg[& \frac{\partial \rho_j}{\partial P_j} \cdot \frac{(1-\rho_L)}{(1-\rho_j)} \cdot f(P_L) \\ & \cdot \left[\sum_{l=j+1}^{L} \prod_{h=j+1}^{L} (1-\rho_h)^{-1} \cdot \Delta_{l-1} + \cdot \Delta_L \right] \\ & + \frac{B_j}{R} \Bigg] = 0. \end{aligned} \tag{10}$$

By substituting $f(P_L, B_L, \Delta_L)$ from (6) into (9) and eliminating λ, we obtain

$$\begin{aligned} & -\frac{\partial \rho_j}{\partial P_j} \cdot (1-\rho_j)^{-1} \cdot \frac{B_L}{R \cdot \Delta_L} \cdot \left(\frac{\partial \rho_L}{\partial P_L}\right)^{-1} \cdot (1-\rho_L) \\ & \cdot \left[\sum_{l=j+1}^{L} \prod_{h=j+1}^{L} (1-\rho_h)^{-1} \cdot \Delta_{l-1} + \cdot \Delta_L \right] + \frac{B_j}{R} = 0. \end{aligned} \tag{11}$$

After some simple manipulations, we obtain, for $j < L$,

$$\begin{aligned} & \left(\frac{\partial \rho_j}{\partial P_j}\right)^{-1} \cdot (1-\rho_j) \cdot B_j \\ & \quad = \left(\frac{\partial \rho_L}{\partial P_L}\right)^{-1} \cdot (1-\rho_L) \cdot B_L \\ & \quad \cdot \left[\sum_{l=j+1}^{L} \left[\prod_{h=l}^{L} (1-\rho_h)^{-1} \right] \cdot \frac{\Delta_{l-1}}{\Delta_L} + 1 \right]. \end{aligned} \tag{12}$$

In the last expression, the left-hand side represents the information related to the jth packet, and it depends on the power of its subsequent packets, $(j+1)$th to Lth. This closed form expression will be used later, in combination with the channel model, for calculating the optimal energy distribution.

Following a similar approach, it is possible to formulate and solve the dual problem, that is, how to transmit the bitstream by minimizing the transmission energy E, subject to a distortion constraint. This problem can be formulated as follows:

$$\min_{P_l} \underbrace{\left\{ \sum_{l=1}^{L} \frac{B_l \cdot P_l}{R} \right\}}_{E}, \qquad \text{s.t. } D_{\text{tot}} = D_0 - E[\Delta], \tag{13}$$

where D_{tot} is the maximum acceptable distortion for the frame. Again, the optimal power assignment must satisfy the same relationship given by (12). The dual problem presented here is useful for applications in which a desired level of visual quality must be maintained using the least amount of energy.

4.2. AWGN channel model

In this section, we consider the transmission of the embedded bitstream through a channel with additive white Gaussian noise (AWGN) by using different digital modulation schemes. Such channel model is considered for its simplicity, even if any channel (multipath, indoor, outdoor) can be considered—given that it is possible to derive the relationship between energy (or power) and probability of error per bit. Moreover, it was demonstrated that AWGN model can be used also in case of CDMA modulation, under specific hypothesis [39].

Since most link-layer protocols discard packets containing errors, from the application point-of-view we can assume that generally the probability of packet loss can be written as the probability of losing at least one bit:

$$\rho_j = 1 - (1 - \varepsilon_j)^{B_j}, \tag{14}$$

where ε is the bit-error probability, which depends on the adopted modulation scheme.

Well-known results from the communication theory [40] provide a relationship between ε and the transmission parameters for different modulations. For the BPSK modulation, for example, ε is given by

$$\varepsilon = Q\left(\sqrt{2 \cdot \gamma_b}\right), \quad \text{with} \gamma_b = \frac{E_b}{N_0}, \tag{15}$$

where E_b is the bit energy, N_0 the noise power per Hz; and the function $Q(x)$ is given by:

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} \cdot e^{-u^2/2} \cdot du. \tag{16}$$

Generalizing, for several digital modulation schemes, the bit-error probability can be written as

$$\varepsilon = a \cdot Q\left(\sqrt{\alpha \cdot \gamma_b}\right), \tag{17}$$

where the values of a and α for different modulations are summarized in Table 2.

Equation (12) can then be expressed as

$$\left(1 - a \cdot Q\left(\sqrt{\alpha \cdot \frac{E_b^j}{N_0}}\right)\right) \cdot \sqrt{E_b^j} \cdot e^{(\alpha \cdot E_b^j)/(2 \cdot N_0)}$$
$$= \left(1 - a \cdot Q\left(\sqrt{\alpha \cdot \frac{E_b^L}{N_0}}\right)\right) \cdot \sqrt{E_b^L} \cdot e^{(\alpha \cdot E_b^L)/(2 \cdot N_0)}$$
$$\cdot \left[1 + \sum_{l=j+1}^{L} \prod_{h=l}^{L} \left(1 - a \cdot Q\left(\sqrt{\alpha \cdot \frac{E_b^h}{N_0}}\right)\right)^{-B_h} \cdot \frac{\Delta_{l-1}}{\Delta_L}\right]. \tag{18}$$

The minimization problem can be solved by finding the value of E_b^L that satisfies the energy constraint. Since it is not possible to provide an analytical closed form solution to the problem, a numerical method is used.

Table 2: Parameters a, α, and the spectral efficiency r_b/B_T for different modulations.

Modulation	a	α	r_b/B_T
FSK	1	1	1
BPSK; PSK	1	2	1
MSK; QAM; QPSK	1	2	2

Once the energy levels for each packet are known, the packet transmission power for packet j can be calculated using the following relationship:

$$P_j = E_b^j \cdot R. \tag{19}$$

4.3. Power control with forward error correction

During video transmission, for increasing the protection of the information stored in the packets, it is possible to add redundancy bits by employing a forward error correction (FEC) code. This operation, usually performed at MAC level in building the MAC frame, enables to recover a given percentage of transmission errors without requiring interaction between the sender and the receiver.

In this section, we address the problem of power control in presence of FEC for optimizing video streams delivery, and analyze the performance of the system in different scenarios. Optimal energy distribution is jointly employed with error correction schemes in order to achieve optimal nonuniform error protection using different modulation schemes. Moreover, the analytical formulation of the proposed framework can be used for estimating the degree of protection offered by power control and FEC, as well as the system sensitivity to the parameters setup. In the remainder of the paper, we will assume that FEC code rate is fixed for all the EL packets—modeling a fixed frame check sequence (FCS) field which is quite common in wireless networks.

A well-known FEC code is the Reed-Solomon code [41], which divides the codeword in m-bit symbols. By its definition, an RS(n, k) code with a codeword of n symbols and k symbols of data can correct up to $t = (n - k)/2$ symbols errors. A symbol represents a sequence of bits, considered as a single "block of information" for the purpose of application of the FEC code.

The probability of packet loss deriving from the employment of an FEC strategy can then be written as the probability of receiving more than t uncorrect symbols, that is,

$$\rho = 1 - \sum_{i=0}^{t} \binom{n}{i} \cdot P_{\text{symbol}}^i \cdot (1 - P_{\text{symbol}})^{n-i}, \tag{20}$$

where P_{symbol} is the error probability for a symbol of m bits, and depends on the bit-error rate ε in the following way:

$$P_{\text{symbol}} = 1 - (1 - \varepsilon)^m. \tag{21}$$

The term ε is the bit-error probability, and depends on the employed modulation parameters and the characteristics of the transmission channel, as described in Section 4.2.

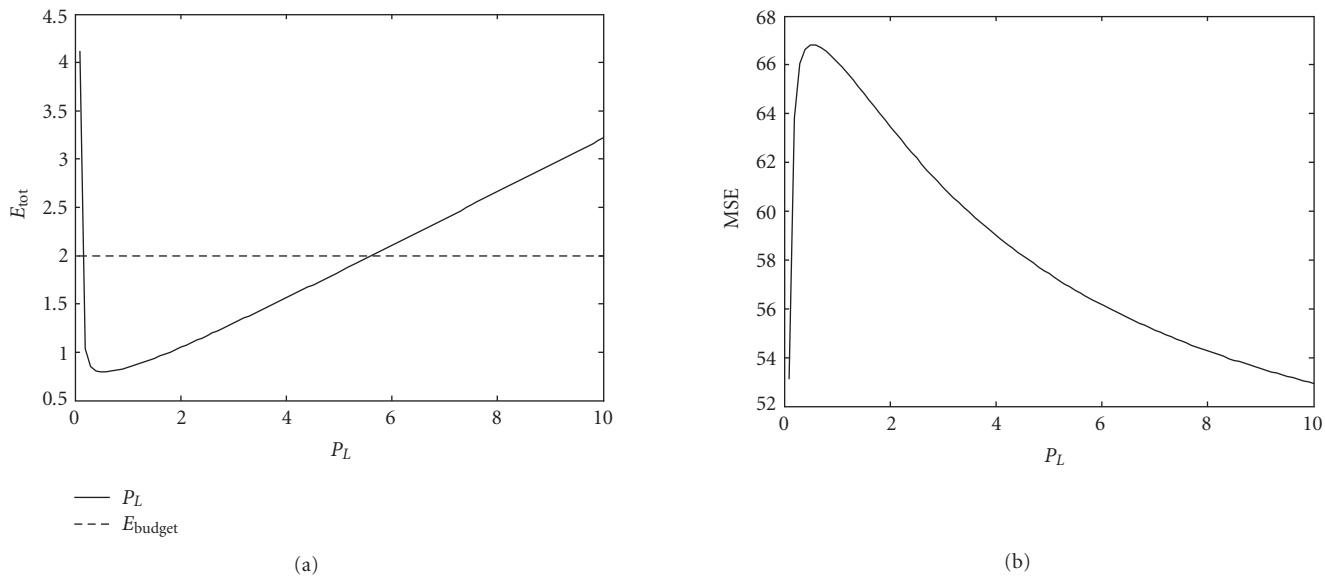

Figure 7: Foreman QCIF sequence, frame 10, equal-size packets: (a) total energy E_{tot} (J) and (b) frame distortion (MSE) (dB) versus the power of the last packet, P_L (W). In (a), the dotted line represents the energy budget.

4.4. Solution for AWGN channel model

As a consequence of the introduction of the FEC schemes, (8) can then be expressed as in the following formula:

$$\frac{\sqrt{E_b^j}\cdot e^{(E_b^j\cdot\alpha)/(2\cdot N_0)}\cdot(1-\varepsilon_j)^{1-m}\cdot(1-\rho_j)}{\sum_{i=0}^{t}\binom{n}{i}\cdot P_{\text{symbol},j}^{i-1}\cdot(1-P_{\text{symbol},j})^{n-i-1}\cdot(i-n\cdot P_{\text{symbol},j})}$$
$$=\frac{\sqrt{E_b^L}\cdot e^{(E_b^L\cdot\alpha)/(2\cdot N_0)}\cdot(1-\varepsilon_L)^{1-m}\cdot(1-\rho_L)}{\sum_{i=0}^{t}\binom{n}{i}\cdot P_{\text{symbol},L}^{i-1}\cdot(1-P_{\text{symbol},L})^{n-i-1}\cdot(i-n\cdot P_{\text{symbol},L})}$$
$$\cdot\left[\sum_{l=j+1}^{L}\prod_{h=l}^{L}(1-\rho_h)^{-1}\cdot\frac{\Delta_{l-1}}{\Delta_L}+1\right]. \tag{22}$$

The minimization problem can be solved by finding the value of E_b^L that satisfies the energy constraint. Indeed, (22) allows to compute the energy to be assigned to the packet j, E_b^j, from those 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 optimal energy distribution $\{E_b^1,\ldots,E_b^L\}$ to be assigned to the packets and the energy budget required for transmitting them.

It is possible then to use (12) to construct a curve $E_{\text{budget}} = f(E_b^L)$ that extrapolates the relationship between the energy budget and the optimal choice of E_b^L.

A numerical algorithm (e.g., the bisection method) can be used to find the value of E_b^L, and thus the optimal energy distribution $\{E_b^1,\ldots,E_b^L\}$, that satisfies the energy constraint. In the case that a solution with E_b^L greater than zero does not exist, the solution of the minimization problem must be searched using $L' = L - 1$ packets.

Once the energy levels for each packet are known, the transmission power for the jth packet can be calculated as $P_j = E_b^j \cdot R$. An example of the numerical approach described above is presented in Figure 7.

5. RESULTS

A number of experiments have been run simulating the transmission of various sequences. Results presented in this section are obtained by simulating the transmission of the QCIF test sequence *foreman*, with a frame rate of 10 fps, noise power N_0 of 10^{-5} W/Hz, and $B_T = 200$ KHz, unless otherwise stated. The sequence is encoded with the MPEG-4 FGS algorithm, setting a fixed bit rate of 14 Kbps for the BL. Packet size is fixed (100 bytes). The maximum number of transmitted EL packets, L, is calculated based on the video frame rate and the available bit rate r_b. The value of r_b depends on the transmission bandwidth B_T and the spectral efficiency of the adopted modulation scheme (Table 2), according to the equation

$$\sigma_e = \frac{r_b}{B_T} \quad (\text{bps/Hz}). \tag{23}$$

Figure 8 presents the results achieved by the proposed optimization approach as compared with equal energy distribution among the packets, in the case of BPSK modulation, for four different test sequences: *foreman*, *carphone*, *salesman*, and *akiyo*. The employed performance metric is the *peak signal-to-noise ratio* (PSNR) at the video decoder, as is usual in video transmission schemes. The proposed solution provides a relevant advantage in error-prone situations, while for an energy value E_{tot} higher than (approximately) 0.5 Joule the performance is similar to equal energy distribution—due to the good performance of the employed

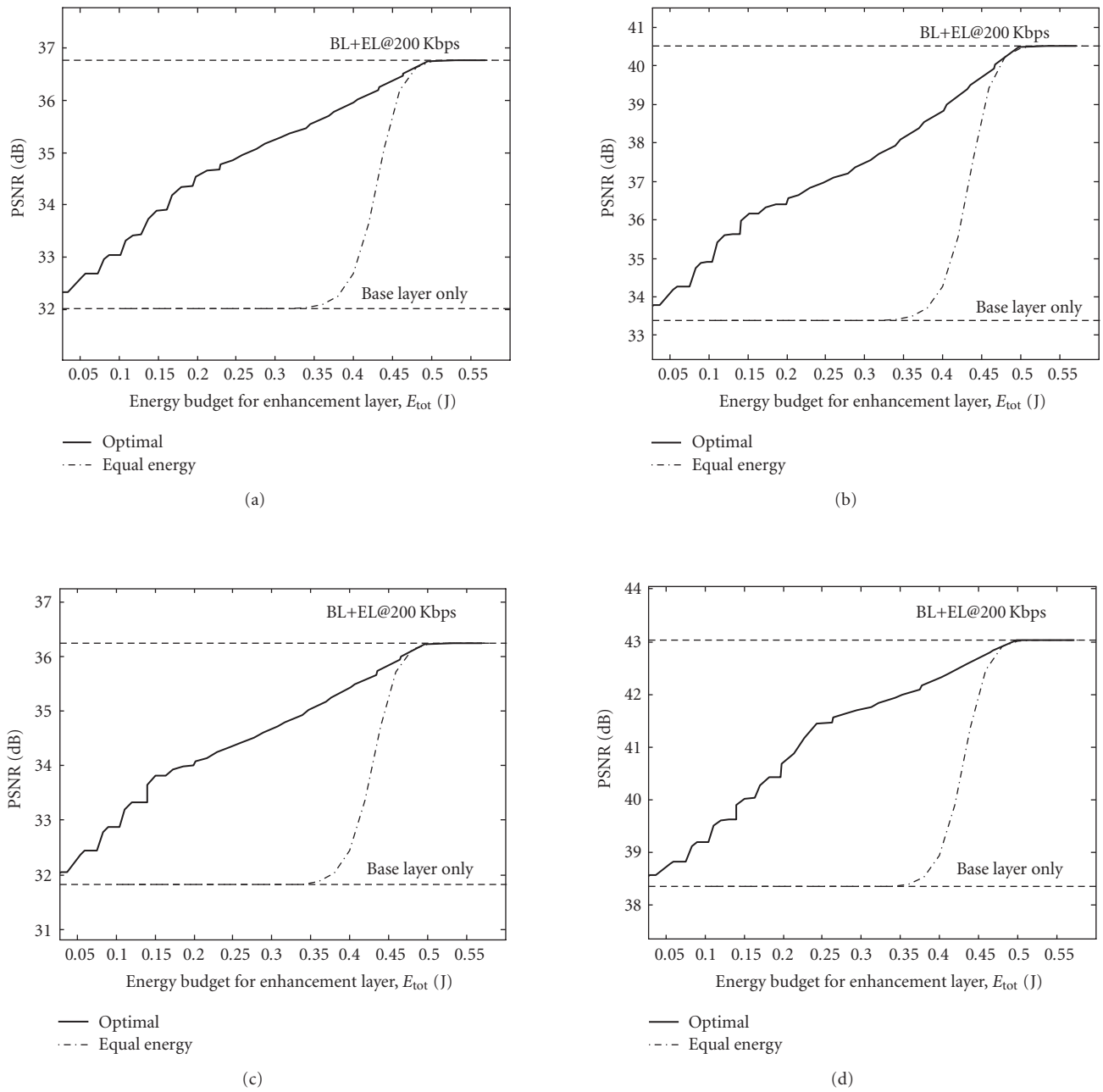

Figure 8: Performance comparison between the proposed approach and equal energy distribution (BPSK modulation, RS(160,100), B_T = 200 KHz). Test sequences are: (a) *foreman*, (b) *carphone*, (c) *salesman*, (d) *akiyo*.

modulation and FEC code. In error-prone situations, the optimal algorithm prefers not to send the less important packets allowing a higher energy protection of the remaining bitstream. This consideration remains valid for all considered test sequences.

This behavior is highlighted for the *foreman* sequence in Figure 9, where a detail on the performance contribution in terms of visual quality is shown for different choices of L.

The impact of different levels of error protection (different FEC code rates) is presented in Figure 10, where the PSNR is plot against the total available energy for two codes with different correction capabilities. Clearly, it is possible to achieve better performance in error-prone scenarios by using a stronger code, at the expense of a lower performance if the channel conditions improve.

Figure 11 summarizes the obtained results for the transmission of a sequence using different modulation schemes (BPSK, MSK, FSK). BPSK achieves better performance than FSK, while MSK provides a higher spectral efficiency, thus allowing transmission of a higher portion of the EL bitstream. Figure 12 demonstrates that the joint employment of FEC codes and power control improves the robustness of the

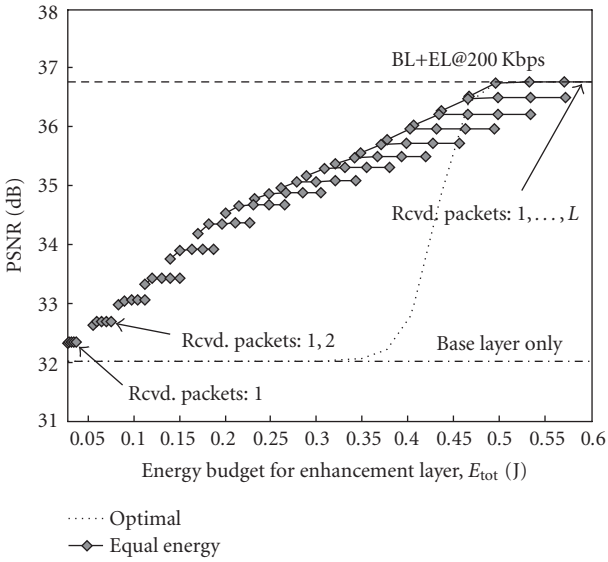

Figure 9: Performance comparison between the proposed approach and equal energy distribution (BPSK modulation, RS(160,100), $B_T = 200$ KHz). Incremental PSNR contribution for each received packet beyond the BL is represented.

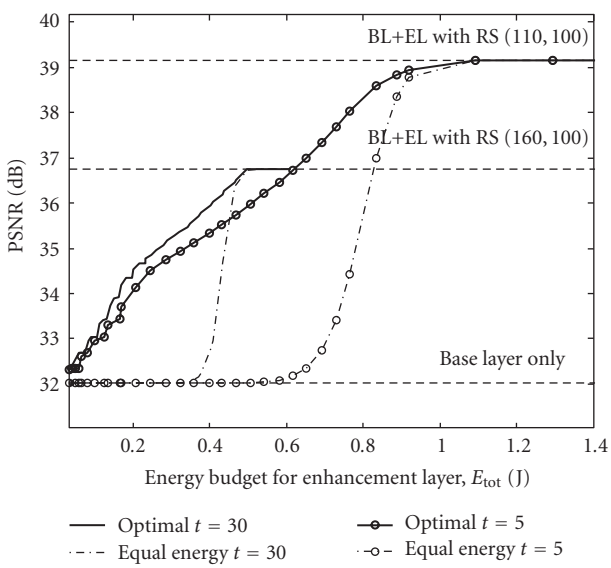

Figure 10: Performance of the proposed approach and equal energy distribution for different RS codes: RS(110,100) and RS(160,100) (BPSK, $B_T = 200$ KHz).

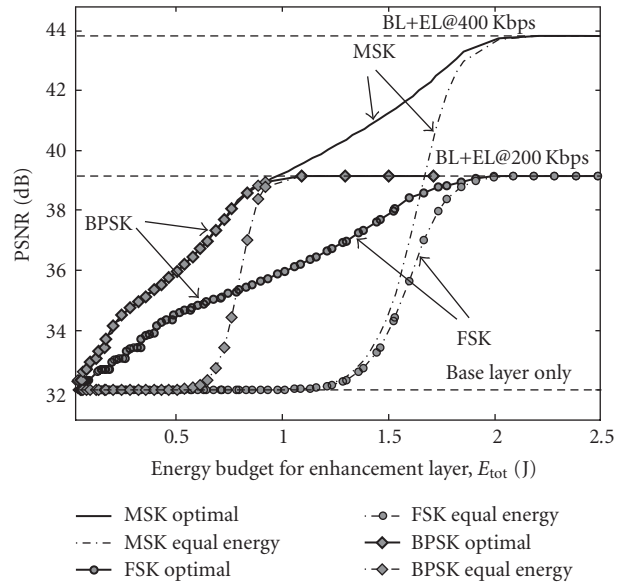

Figure 11: Comparison among different modulation schemes (BPSK, FSK, and MSK) in terms of PSNR at the receiver (RS(110,100), $B_T = 200$ KHz).

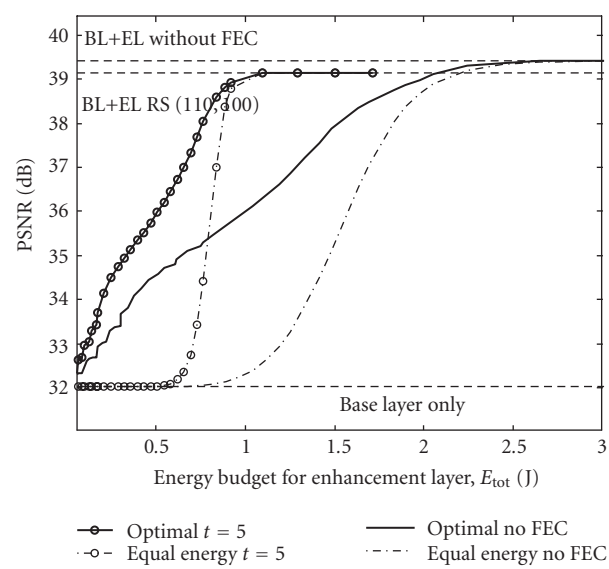

Figure 12: Performance improvement deriving by the introduction of RS(110,100) code (BPSK, $B_T = 200$ KHz).

video stream. On the other hand, equal energy distribution is characterized by a step-like behavior, making it very sensitive to changing channel conditions—especially if FEC is employed.

Finally, Figure 13 summarizes the obtained results, comparing the considered cross-layering approach (UEP) with equal energy distribution (EEP). This allows us to conclude that there is a relevant advantage in the employment of optimized power control and forward error correction—especially when the available energy budget is limited, while above a certain level of available transmission resources transmission is reliable and thus unequal protection (and cross-layering) is less valuable. Moreover, the introduction of FEC makes the performance more sensitive to the available power, and as a consequence requires reliable estimation of the state of the channel.

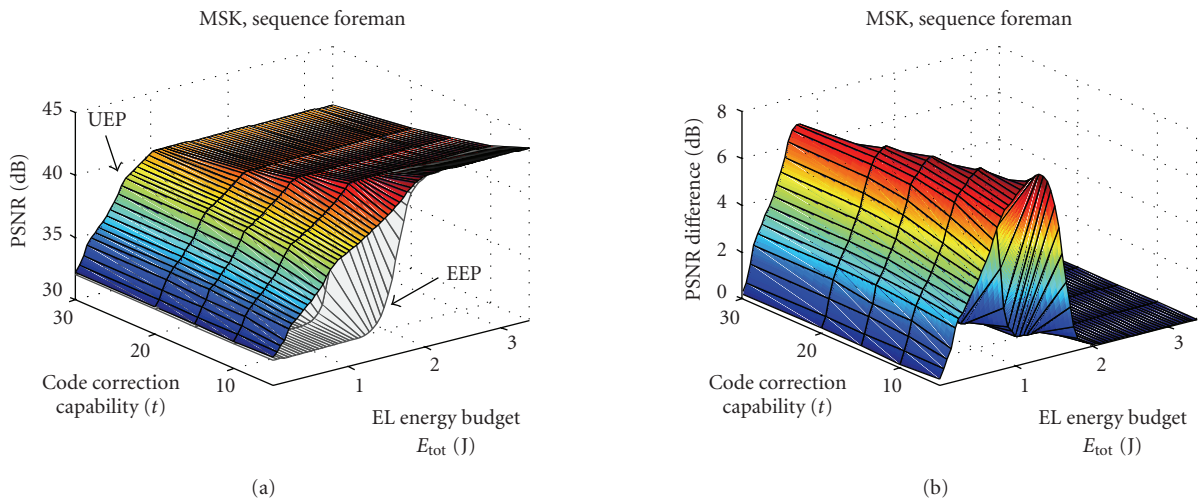

Figure 13: PSNR performance of cross-layer UEP (a) and improvement against EEP (b) versus energy budget and code correction capability of FEC.

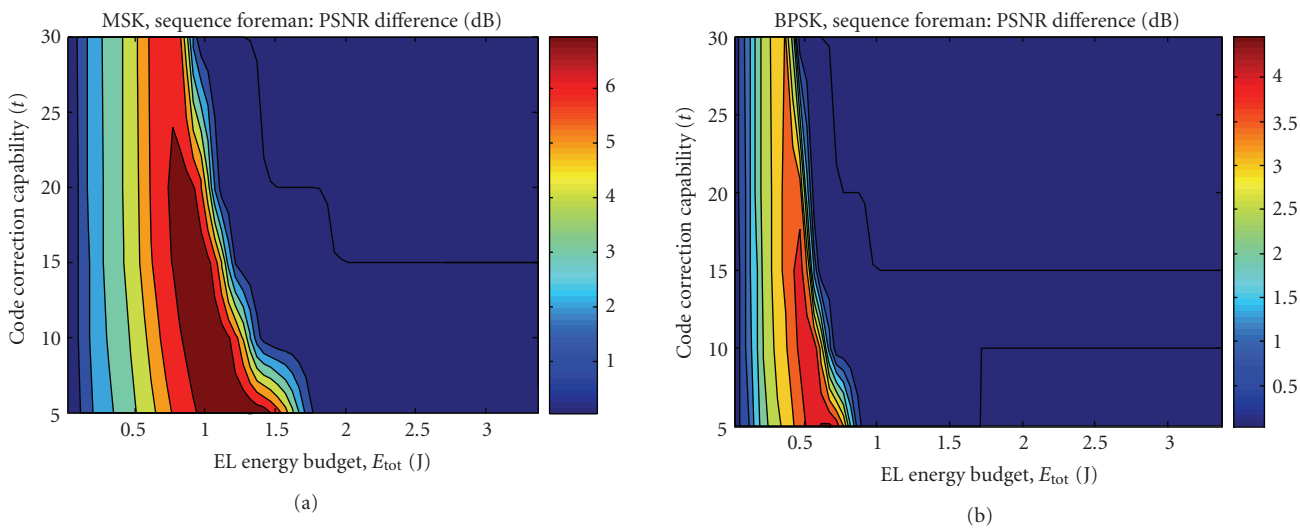

Figure 14: Performance gain of cross-layer UEP against EEP for MSK (a) and BPSK (b) modulations.

Summarizing, from the analysis of our model we conclude that cross-layering oriented towards unequal error protection can provide a relevant performance gain, especially for limited availability of transmission resources (energy budget lower than 2 Joules in Figure 13) or in the case of a very noisy channel. In particular, interaction between the video encoder and power control is advisable for power-constrained devices, while FEC should be considered more carefully since it is making the system more sensitive to channel conditions, even if it could provide additional power saving. This aspect is further illustrated in Figure 14(a), which represents a different view of the graph in Figure 13(b). Figure 14(b) underlines that similar behavior holds for other modulations as well (BPSK in particular).

Finally, Figure 15 provides a comparison among different modulation schemes (FSK, MSK, and BPSK) in terms of energy spent against maximum achievable PSNR gain. The curves are plot for different correction capabilities of the code (t). The graph clearly outlines that maximum power savings is achieved by using BPSK (providing the optimal parameter settings, as well), while the highest gain (more than 7 dB against EEP, more than 3 dB against BPSK) derives by the employment of MSK at the expense of a slightly higher energy consumption.

As a final remark regarding the possible implementation of a system supporting the proposed cross-layered architecture, the complexity of the devices will need to be increased (with reference to the fully layered architecture) mainly to support interaction between the source encoder and the link and physical layer protocols, in order to enable information exchange. The process of optimization does not severely impact on the complexity of the resource-constrained video

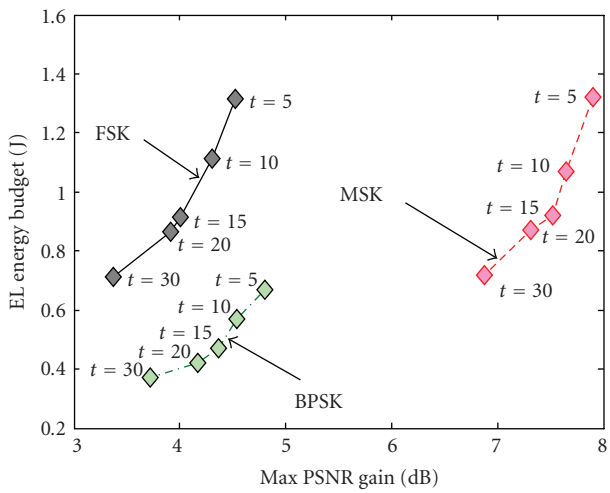

Figure 15: Relationship between PSNR gain of cross-layer UEP strategy against EEP and available energy budget.

device, since having a suitable R-D model of the video source (which is likely, i.e., in the case of surveillance applications) the whole process can be performed offline and then allow adaptive power and FEC allocation on the basis of a simple lookup table for each EL packet.

6. CONCLUSIONS AND FUTURE WORK

Cross-layering is an interesting design paradigm, recently proposed to overcome the limitations deriving from the ISO/OSI layering principle in order to improve performance of communications in specific scenarios, such as wireless multimedia communications. However, most available solutions are based on empirical reasoning, and do not provide a theoretic background supporting such approaches. The paper provides an analytical framework for the study of single-hop embedded video delivery over a wireless link, enabling the study of cross-layer interactions for performance optimization using power control and FEC and providing a useful tool for determining the potential benefits of such architecture. From analysis of the achieved results, the following remarks can be derived: (i) cross-layering is necessary to allow video transmission in presence of limited transmission resources (bandwidth, power); (ii) introduction of FEC codes brings relevant performance gains, but performance becomes more sensitive to available energy budget; (iii) adaptation of transmission power and FEC based on R-D model provides more benefits than independent usage of power control or FEC, supporting a wider range in terms of energy budget.

Future work will deal with the analysis of more complex scenarios (such as in presence of link-layer retransmissions, multihop communication) and with the investigation on the definition of an end-to-end R-D model for multihop video transmission.

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