Optimal power control for embedded packet video transmission over WiFi

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Abstract—Video transmission over wireless links is becoming an interesting issue in modern communication networks. The paper presents a framework for modeling and providing an optimal solution to the problem of power control in transmission of embedded video over a single Wi-Fi link. The approach, based on a constrained optimization problem, is then compared with equal energy distribution, demonstrating significant regions of enhancement.

Keywords — IEEE 802.11, power control, wireless video transmission

I. INTRODUCTION

Delivery of multimedia streams over wireless networks (or in heterogeneous networks comprising wireless links) is a challenging issue, since it involves several problems related to mobility, such as the relatively high percentage of transmission errors in the wireless medium and the limited energy of portable devices.

Research advances in the field of multimedia representation and encoding lead to the construction of embedded bitstreams, which are included in various multimedia coding algorithms, and have the advantage of being partially decodable (in case of bitstream truncation). This approach can be introduced in video coding by implementing several techniques, such as wavelets and bitplane coding. In the MPEG-4 [1] such concepts are implemented in the Fine Granularity Scalability (FGS) scheme [2], where video data are partitioned into two bitstreams: a Base Layer (BL) and a progressively coded Enhancement Layer (EL). The BL, when decoded alone, generates a low resolution version of the original sequence. When decoded together to the EL, or even a truncated part of it, additional information is supplied in order to obtain a detailed version of the data.

In this paper, the problem of power-controlled video transmission over Wi-Fi (IEEE 802.11b [10]) links is considered. In order to achieve efficient delivery, we take advantage of the structure of embedded bitstreams for implementing packet prioritization based on a non-uniform allocation of the available transmission energy supported by the usage of forward error correction (FEC) codes. This allows extension of previous work of the authors [4, 6, 11] to a realistic and effective modeling of frame-level video-over-Wi-Fi transmission.

The structure of the paper is the following: Section II provides an in-depth description of the proposed approach, while Section III analyses the achieved results. Finally, Section IV concludes the paper with final remarks and outlines about future work on the topic.

II. DESCRIPTION OF THE PROPOSED APPROACH

A. The Considered Scenario

In the considered scenario, a mobile terminal within a Wi-Fi cell needs to transmit a video...
sequence to a video server located somewhere in the Internet (see fig. 1). We are interested in studying the optimal power allocation procedure in order to provide satisfactory video quality and proper energy saving within the single-hop uplink transmission between the mobile node and the Wi-Fi Access Point.

In order to provide the required functionality, an additional power control module needs to be implemented within the IEEE 802.11b interface of the mobile terminal, which controls the power allocated to each EL video packet on the basis of information provided by the MPEG-4 video encoder and Wi-Fi Radio MAC modules.

Signal-To-Noise (SNR) information is required for effective power control since it enables to estimate the status of the channel. Several works discussed how to properly estimate SNR on an IEEE 802.11 link, like [12] and [13]. 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 [13] to use the SNR of the last ACK frame as an indication of the SNR at the other side. Therefore, in the following paragraphs we will assume that SNR information can be directly calculated by the Wi-Fi MAC protocol.

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

B. MPEG-4 FGS

In the considered scenario, video is encoded using the MPEG-4 FGS scheme. In MPEG-4 FGS, scalability is provided in two ways. First, the video is encoded into two separate bitstreams: the Base Layer (BL) and the Enhancement Layer (EL). The BL, which provides a low quality, low bitrate, representation of the data, is independently encoded as a standard baseline MPEG-4 bitstream. Then, the difference between the BL and the original sequence is encoded in the EL, which provides additional information to the former bitstream. Fine granular scalability is provided by the EL itself, since residual data are block-encoded and the DCT coefficients are bit-plane coded, thus generating an embedded bitstream.

![Figure 1. The scenario considered in the paper.](image1)

![Figure 2. Block scheme of the main components at the mobile terminal side.](image2)
The quality contribution given to the BL by the data coded in the EL bitstream decreases as we go from the most significant bit plane (MSBP) to the least significant one (LSBP). At the same time, data from MSBP are easier to compress, since it are more correlated, than data from the LSBP, as it is shown in the characteristic rate distortion (RD) curve [6].

The advantage of having this type of EL is that, in the case the bitstream is truncated, it can still be decoded and the obtained data used to add information to the BL (Fig. 3). As a result, 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.

![Figure 3. Example of rate control applied to FGS bitstream.](image)

This coding approach can simplify rate control algorithms implementation and can be used in combination with unequal error protection policies [3, 8].

C. Problem Statement

We assume that the BL is correctly received. Correct reception of the BL is not a strong assumption: as shown in [3], a packet loss lower than 1% for the BL does not affect the overall FGS performance. Moreover, since its size is very small as compared to the EL (a few packets), it is possible to better control the probability of losing BL packets such that it can be considered arbitrarily small (e.g. by using retransmissions and strong protection).

Our goal, given the maximum amount of energy $E_{tot}$ per EL of each frame, is to determine how to allocate the available energy in presence of different FEC codes in such a way to minimize the overall distortion at the receiver.

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

$$\min_{E_k} \left\{D_{BL} - E[\Delta_{EL}] \right\} \quad s.t. \quad E_{tot} = \sum L \cdot B_i \cdot E_b^i$$  \hspace{1cm} (1)

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

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:

$$E[\Delta_{EL}] = \sum_{i=1}^L \prod_{i=1}^L (1 - \rho_i) \cdot \Delta_i$$  \hspace{1cm} (2)

where $\rho_i$ is the loss probability for the $i$-th packet, and $\Delta_i$ is the distortion improvement introduced by its availability.

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

$$\min_{E_b} J =$$

$$\min_{E_b} \left\{D_{BL} - \sum_{i=1}^L \prod_{i=1}^L (1 - \rho_i) \cdot \Delta_i + \lambda \left( \sum B_i \cdot E_b^i \right) \right\}$$  \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 $i$-th packet $\rho_i$ and the energy $E_b^i$ used for transmitting it is known at the transmitter:

$$\rho_i = g(E_b^i)$$  \hspace{1cm} (4)
where the function $g$ can be defined using an analytical model of the wireless channel and of the employed modulation scheme.

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:

$$\frac{\partial J}{\partial E_b^j} = (1 - \rho_j)^{-1} \sum_{l=1}^{L} \left( \prod_{i=1}^{j} (1 - \rho_i) \right) \Delta_j + \lambda \cdot B_L = 0 \quad (5)$$

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 $L$:

$$\left( \frac{\partial \rho_j}{\partial E_b^j} \right)^{-1} (1 - \rho_j) \cdot B_j = \left( \frac{\partial \rho_L}{\partial E_b^L} \right)^{-1} (1 - \rho_L) \cdot B_L \left[ \sum_{j=1}^{L} \left( \prod_{i=1}^{j} (1 - \rho_i) \right) \frac{\Delta_j}{\Delta_L} + 1 \right] \quad (6)$$

D. Modeling Wi-Fi at the MAC level

The video bit-stream is transmitted in frames on the wireless link, following the IEEE 802.11b (Wi-Fi) standard for WLANs [10]. IEEE 802.11b specifies data transmission using the MAC frame structure presented in Figure 4. In details:

- Physical Layer Convergence Protocol (PLCP) information (24 bytes in total for preamble and header) are always transmitted at 1Mbps (basic rate), in order to convey information about the datarate employed in the remainder of the frame;
- MAC header (30 bytes) contains information related to source and destination + control information;
- Data field encapsulates PDUs (Protocol Data Units) provided by upper layers;
- Frame Check Sequence (FCS, 4 bytes) provides robustness against isolated bit errors, and it is applied on the MAC header and data payload by a CRC-32 code [15]. This enables to recover a given percentage of transmission errors without requiring interaction between the sender and the receiver.

![Figure 4. Wi-Fi frame format.](image-url)

Access to the channel is performed using CSMA/CA plus (optional) RTS/CTS exchange, where a terminal is allowed to transmit data only if the medium remains idle for at least an interval equal to DIFS. Flow control is essentially “Stop&Wait”. For more information about the standard, the reader should refer to [10].

In the following model, we assume to allow only a single frame transmission, thus neglecting the usage of frame level retransmissions, since we want to avoid power consumption deriving from multiple retransmissions. Furthermore, power control is restricted to the MAC + Data + FCS fields: PLCP preamble and header are not included in the energy budget $E_{tot}$ in order to maintain Wi-Fi compatibility.

Finally, we suppose to employ a Reed Solomon (RS) code [5] as FCS – in order to provide error correction capability at the receiver. 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. The probability of packet loss can be written as the probability of receiving more than $t$ un-correct symbols:

$$\rho = 1 - \sum_{i=0}^{t} \binom{n}{i} \cdot P_{\text{symbol}}^i \cdot (1 - P_{\text{symbol}})^{n-i}, \quad (7)$$

where $P_{\text{symbol}}$ is the error probability for a symbol of $m$ bits, and depends from the bit error rate $\varepsilon$ in the following way.

$$P_{\text{symbol}} = 1 - (1 - \varepsilon)^m \quad (8)$$

The term $\varepsilon$ is the bit error probability, and it depends from the employed modulation parameters and the characteristics of the transmission channel.

E. Wi-Fi Modulation and Channel Models

Wi-Fi employs Direct Sequence Spread Spectrum (DSSS) modulation. In the following we consider the model developed by Turin in [9] for Direct Sequence CDMA systems on single-path non-fading
links. In Turin’s model, the signal-to-noise ratio at the receiver side can be approximated as:

\[
SNR = \left[ \frac{N}{3M} + \frac{N_0}{2E_{b,r}} \right]^{-1}
\]

where \( N \) is the number of interfering users, \( M \) the no. of chips per bit, \( E_{b,r} \) is the received bit energy, \( N_0 \) is the noise power per Hz.

As a consequence, the probability of error per bit is given by

\[
\epsilon = \frac{1}{2} \exp \left[ -\frac{1}{2} \left( \frac{N}{3M} + \frac{N_0}{2E_{b,r}} \right)^{-1} \right]
\]

In case of multipath fading links, instead, the per-path SNR can be approximated as:

\[
\frac{\tilde{E}_{b,LOS}}{N_0} = \frac{E_{b,r}/N_0}{1 + 8N_0 \left( \frac{E_{b,r}}{N_0} \right)}
\]

F. Solution of the Problem

By introducing Eq. (10) in Eq.(6) we obtain the following:

\[
\frac{\partial \rho}{\partial E_b} = \sum_{i=1}^{n} \left( \frac{N}{3M} - \frac{\gamma_i}{\gamma_i + 1} \right) \frac{1}{\epsilon_i} B_i
\]

\[
\frac{\partial \rho}{\partial E_b} = -m \sum_{i=1}^{n} \left( \frac{N}{3M} - \frac{\gamma_i}{\gamma_i + 1} \right) \frac{1}{\epsilon_i} B_i
\]

As a consequence, Eq. (6) can then be expressed as in the formula at the bottom of the page (13), where \( n_j = B_j/m \) is the size of the \( j \)-th packet expressed in number of symbols.

The minimization problem can be solved by finding the value of \( E_b^L \) that satisfies the energy constraint. Indeed, eqn. (12) 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 then possible to use equation (13) to construct a curve \( E_{budget} = f(E_b^L) \) 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 then 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 \( j \)-th packet can be calculated as \( P_j = E_b^j \cdot R \).

III. EXPERIMENTAL RESULTS

Presented results are achieved by simulating (in Matlab) the transmission of the QCIF test sequence for a 10 fps. Other video sequences (mobile&calendar, mother&daughter, ...) provided similar results, which are not presented for space constraints. Video is encoded with the MPEG-4 FGS algorithm, setting a fixed bitrate of 14Kbps for the BL and maximum size of the EL to 100Kbps and 400Kbps. Payload size is kept fixed for each experiment. Noise power \( N_0 \) is set to \( 10^{-5} \)w/Hz. The maximum number of transmitted EL packets, \( L \), is calculated based on the video frame rate and the available bit rate \( R_b \).

\[
\sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i = \frac{1}{\epsilon_i} B_i \sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i 
\]

where \( \sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i = \frac{1}{\epsilon_i} B_i \)

\[
\sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i = \frac{1}{\epsilon_i} B_i \sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i 
\]

\[
\sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i = \frac{1}{\epsilon_i} B_i \sum_{i=1}^{n_j} \left( 1 - \rho_i \right)^{n_j \cdot \gamma_i} \cdot \frac{N}{3M} \cdot \gamma_i \cdot B_i 
\]
Main result is presented in Fig. 5, where peak signal-to-noise ratio (PSNR) of the received video is plotted against the energy allocated to the EL (encoded at 100Kbps).

The proposed approach (UEP - optimal) provides a relevant enhancement in terms of performance over equal energy distribution (EEP), which avoids the steep slope located at around 0.8 joules. As a consequence, the usage of power control enables to reduce the sensitivity of the system (i.e. a small variation of the allocated energy has less impact on UEP rather than on EEP).

From a numerical analysis of Fig.5 it is possible to underline a relevant increase in received quality, in some cases higher than 2-3 dB. Furthermore, Fig.5 underlines the effect of dropping one packet when the total energy is not enough for transmitting all the packets in an efficient way: in this case, the system optimizes the transmission for $L' = L - 1$, obtaining the optimal result.

Figure 6 presents performance comparison between UEP and EEP for different MAC-level payload size (200 and 400 bytes). It can be noticed that performance gain of UEP on EEP remains almost the same. However, increasing the payload size (see Fig. 7, the performance of UEP becomes more sensitive to the available energy – underlining a step-like behavior.

Finally, Figure 8 underlines the potential benefits of introducing error correction by using RS instead of CRC-32.

IV. CONCLUSIONS AND FUTURE WORK

Summarizing, the proposed framework enables analytical modeling of a video-over-wireless application and provides an optimal solution to the problem of power control in presence of link-level framing. The approach is validated by comparing performance with equal energy distribution in case of operation on a single-path non fading link, demonstrating significant regions of enhancement.

Future work on the topic is related to test the proposed approach in the framework of the H.264 SVC [14], as a novel video coding scheme, currently under development, and to identify a more precise model of link level framing, by considering ARQ flow control strategies.

REFERENCES


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Figure 5. Comparison between EEP and UEP (with FCS).

Figure 6. Comparison between EEP and UEP for different MAC Layer payload size (200 and 400 bytes).

Figure 7. Comparison between EEP and UEP for different MAC Layer payload size (400 and 800 bytes).

Figure 8. Comparison between EEP and UEP (with and without FCS).