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Cross-layer Optimization of Unequal Protected Layered Video over Hierarchical Modulation

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***Abstract*—Unequal protection mechanisms have been proposed at several layers in order to improve the reliability of multimedia contents, especially for video data. The paper aims at implementing a multi-layer unequal protection scheme, which is based on a Physical-Transport-Application cross-layer design. Hierarchical Modulation, in the physical layer, has been demonstrated to increase the overall user capacity of a wireless communications. On the other hand, unequal erasure protection codes at the transport layer turned out to be an efficient method to protect video data generated by the application layer by exploiting their intrinsic properties. In this paper, the two techniques are jointly optimized in order to enable recovering lost data in case the protection is performed separately. We show that the cross-layer design proposed herein outperforms the performance of hierarchical modulation and unequal erasure codes taken independently.**

***Index Terms*—Unequal erasure protection (UEP), Hierarchical Modulation, cross-layer, data dependencies, multicast, video distorsion.**

I. Introduction

Mobile multimedia services are one of the most promising key applications for next wireless systems. On the market side, users put pressure on service providers to add more applications than the system was originally designed for. On the technical side, new cost-efficient solutions have to be developed not only to allow higher bit rate to be transmitted through the same channel, but also to adapt to channel conditions in order to fulfil the QoS requirements of users. However, this becomes a difficult issue due to the changing nature of wireless channel, which has a great impact on the system design. Specially relevant is the mobile scenario, where multiple fading types need to be mitigated. Moreover, the intrinsic problem of multi-user channel diversity among a group of wireless receivers makes it a huge challenge to determine an effective transmission strategy at a the transmitter.

Exhaustive research has been carried out on protection schemes solutions for wireless communications by exploiting the protocol designs, bandwidth efficiency, etc. However, most of them follow the traditional layered architecture, where they achieve high performance but only according to each individual layer and its corresponding set of features. Cross-layer designs have been demonstrated to jointly optimize the overall network performance by taking advantage of the available features of different layers. In wireless communication networks, big efforts using cross-layer designs have been carried out in order to comply with the stringent QoS requirements [1], [2], however cross-layer protection schemes has not yet been exploited in depth, and even less using the above proposed techniques. In this paper, we propose a new cross-layer design, which merges the use of Hierarchical Modulation (HM) at the physical layer, with unequal erasure codes at the transport layer in order to optimize the protection of scalable multilayered video data generated at the application layer. This is particularly attractive since it allows following a joint strategy in order to fulfill QoS requirements in terms of lost packets for different types of users, which at the same time can be seen as a multicast tranmission. Herein, multicasting is understood at system level instead of at networking level. Receivers are organized in groups according to the channel conditions, and the transmission strategy is optimized for every group.

Included in several standards, such as DVB-T, DVB-H, and the recently standardized DVB-SH and WiMAX (IEEE 802.16), in [3], we have demonstrated that HM is an efficient transmission mode achieving better system performance and customer experience than other solutions. Note that HM is known as the practical implementation of the Superposition Coding (SC) scheme, where different receivers can decode at different rates within the same transmission over the wireless channel depending on the power allocation and channel attenuation. In such scenario different data streams are sent using different power. Users with good reception can demodulate multiple layers, on the other hand, users with poor reception condition are only able to demodulate the data stream embedded in the base layer, and it is affected by the interference produced by the other streams. SC has been shown to be optimal [4] only for a degraded broadcast channel, where all users can be sort depending on the channel attenuation, and its practical implementation (i.e. HM) obviously outperforms many deployed systems with fixed modulation schemes. Note that physical layer adaptation could be applied to counteract fading, however a disadvantage of such a solution is that it might require receivers with expensive and complex features. Moreover, opposite to HM schemes, they are not usually backward compatible, i.e. the upgraded system is not transparent to the already deployed receivers of the original system, and thus we do not consider it here.

One major limitation of hierarchical modulation is that it has been standardized only for a two layer scheme, which reduces the diversity of the transmission (only two quality levels). In [5], it is showed that the 2-level SC achieves part of the throughput gain in a quasi-static Rayleigh Channel, however, it might vary depending on channel conditions. Thus, in order to compensate this low granularity at the physical layer, we take advantage of the scalable video codes at higher layers.

At the Application layer, we consider Fine Granularity Scalability (FGS), a development in the design of video coding mechanisms. The main goal of this solution is founded in video streaming, where its flexibility is increased [6]. With FGS coding, the video is encoded into a base layer and one enhancement layer. Similar to conventional scalable video coding, the base layer must be received completely in order to decode and display basic quality video. However, in contrast to conventional scalable video coding, which requires the reception of complete enhancement layers to improve on the basic video quality, with FGS coding the enhancement layer stream can be cut anywhere at the granularity of bits before transmission. The received part of the FGS enhancement layer stream can be successfully decoded and improves on the basic video quality. With the fine granularity property of the enhancement layer, FGS encoded videos can flexibly adapt to changes in the available bandwidth in wired and wireless networks. As we will show in next sections, we will take advantage of the hybrid temporal-SNR scalability. In addition to unequal protection at PHY and APP, we also consider erasure codes at the Transport layer, which allows recovering lost packets thanks to redundant information. These codes can be adapted to the data properties by allocating more protection to specific parts of the data. Several works have addressed this issue [7]-[10], based on Priority Encoding Transmission (PET), which allows the sender to decompose the data into classes of given importance. However we focus on a data protection scheme that integrates the dependencies at the packet-level by keeping the data dependencies produced by the source. In particular, we focus on Dependency-Aware Unequal Erasure Protection (DA-UEP) codes studied in [11], where it is presented a different approach for protecting multi-classes data by generating specific redundancy according to existing dependencies in MPEG4 streams. This solution integrates the data dependencies at data-level, in particular within the construction of the Cauchy generator matrix, which is used to encode the defined erasure code.

Thus, the cross-layer protection scheme proposed herein will take profit not only of the granularity available at APP level with FGS, but also at physical layer, allowing for multicast groups differentiation. The paper is organized as follows. A description of the techniques (SC and DA-UEP) is provided in section II, defining also the optimization parameters to be considered per layer. Section III presents the cross-layer architecture, including the channel suppositions taken into account. The joint cross-layer design is fully detailed in the first part of section IV. Next, the results will be analyzed in depth, comparing the cross-layer design with the non cross-layer for different design parameters. Finally, in the conclusion, we identify the achievements and the issues to be addressed in the future.

II. Unequal Per-Layer Protection Models

A. Hierarchical Modulation

More than thirty years ago, [12] showed that one strategy to guarantee basic communications in all conditions is to divide the transmitted information into two or more classes, and to give every class a different degree of protection, which is the principle of SC. The goal is that the most important information (basic) can be recovered by all receivers, while the less important (refinement) can only be recovered by best users. SC along with Dirty Paper Coding (DPC) are the theoretical transmission configurations that achieve the capacity region of wireless communications systems.

One of the practical ways investigated to perform the principle of SC is based on Hierarchical Modulation, where two separate data streams are modulated onto a single stream. One stream, called high priority stream is embedded within a low priority stream. Receivers in good reception conditions can receive both streams, while those with poorer reception conditions may only receive the high priority stream. E.g., in DVB-SH standard, the hierarchical system maps the data onto the 16QAM in such a way that there is effectively a QPSK stream (high priority) buried within the 16QAM stream (low priority). The QPSK/64QAM is another common hierarchical scheme used in DVB-T.

Although the concept of this paper may be applied to all types of Hierarchical Modulation, we will focus on a typical QPSK/16QAM transmission scheme (as standardized in DVB-SH [13]) as depicted in Fig. 1. We will focus on Bit Error Rate (BER) to evaluate the performance of this scheme and also to detect the parameters to be optimized in the physical layer. Several approximate BER expression are available, such as in [14], but they underestimates BER at low SNR, and for fading channels, the performance is severely degradated. Therefore we will use the exact expressions from [15].

From the distances d_1 and d_2 defined in Fig. 1, we can obtain the average energy per symbol (E_s), given by:

$$E_s = 2d_1^2 + 2d_2^2 \quad (1)$$

where the first term represents the average energy per symbol of the QPSK modulation with symbols separated by $2d_1$. The bit error probability for users decoding QPSK and 16QAM modulations in a hierarchical system are defined as (2) and (3) respectively.

$$BER_{QPSK} = \frac{1}{4}\left(U(1,-1) + U(1,1)\right) \quad (2)$$

$$BER_{16QAM} = \frac{1}{4}\left(2U(0,1) + U(2,-1) - U(2,1)\right) \quad (3)$$

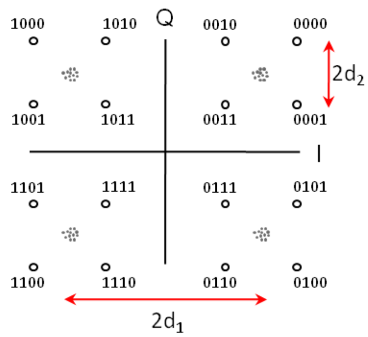

Fig. 1. QPSK/16QAM Hierarchical Modulation Scheme, where noise emulates the symbols received by QPSK users

where

$$U(a,b) = erfc\left(\frac{ad_1 + bd_2}{\sqrt{N_o}}\right) \quad (4)$$

Several conclusions can be extracted from the equations above. First of all, the first term of (2) and (3) are known as the BER approximations of each type of receiver. Considering only the first term of (2) (i.e. the approximation), we can stress that the performance of QPSK users in a hierarchical system is degraded in terms of BER by d_2, if we compare it with the BER when they are placed in a non-hierarchical system (5).

$$BER_{QPSK'} = \frac{1}{2}\left(erfc\sqrt{\frac{E_s}{2N_o}}\right) = \frac{1}{2}\left(erfc\frac{d_1}{\sqrt{N_o}}\right) \quad (5)$$

d_1 and d_2 are the parameters to be considered when designing a hierarchical modulation scheme. More interesting is the ratio $\lambda = d_2/d_1$, which allows us to characterize the system for a given E_s, which is hierarchical when $0 < \lambda \leq 1/2$. For high values of λ, 16QAM receivers experience better BER performance, opposite to QPSK users, which are clearly affected by the hierarchical distorsion. Note that if $\lambda = 1/2$, it is the uniform hierarchical modulation, and if $\lambda = 0$, it is the fixed modulation QPSK system.

Therefore, although the hierarchical scheme can increase the system capacity, it degradates QPSK users in terms of bit error probability, and thus it is necessary to find a trade-off between PER and overall throughput capacity.

B. DA-UEP for Transport Layer

Video data have specific properties and constraints that must be taken into account in the design of reliability systems. One example of these properties is that video decoder can support a low packet erasure rate (up to 5%) by implementing error concealment mechanisms. On the other hand, these streams often require constraints in terms of delay, *e. g.* for video conferencing or video streaming.

The internal structure of the stream generated by a video encoder has particular properties leading to unequal importance of packets carrying the video frames and to dependencies between these packets.

A classical type of such dependency is generated by FGS encoder [6] (see Section I) where the base layer must be first received and decoded in order to use enhancement layers. A second type of dependencies occurs in "natural" video streams (*e. g.* MPEG/H.264) composed of I-frames (intra-coded pictures) and P and B inter-frames. The two last types of frames are encoded from the previous P or I frame, and from the previous and the next frame respectively.

Dependency-Aware unequal erasure protection (DA-UEP) introduced in [11] can be applied to any type of data containing dependencies between the data units to be protected. For the sake of simplicity, we present this system only for streams of intra and inter-frames.

DA-UEP codes are block codes that aim at protecting a set of K data units by generating $N-K$ redundancy packets. Its originality is to integrate the intrinsic dependency relationships between the data units in the construction of the redundancy packets. This integration is done by applying a simple set of rules to each generated redundancy packet. These rules can be expressed as follows: a redundancy packet protecting a packet belonging to the frame t must :

1) protect all the packets belonging to this frame
2) protect all the frames (i.e. all the packets belonging to those frames) on which this frame depends.

Considering the dependency relationships that hold within a Group of Pictures (GOP) containing one I-frame and several P and B inter-frames, by applying the above defined rules to these data, it is possible to generate several kinds of redundancy packets.

- *The rddce_I* type : Packet protecting the I frame
- The *rddce_IP* type : Packets protecting a P frame and all the precedent P frames until the first I frame.
- The *rddce_IPB* type : Packets protecting a B frame, the corresponding pair of reference frames and all frames on which they depend.

The parameters r_I and r_P respectively denotes the number of packets of types *rddce_I* and *rddce_IP*. The number of packets of *rddce_IPB* type is then equal to $n-k-r\_I-r\_P$.

A simple way of implementation is to encode data on a GOP basis, i.e. it is assigned a certain amount of redundant data to each GOP. Moreover, the shape of the generator matrix is closely related to the size of each frame of the GOP. Hence, by knowing that the size of a frame varies from GOP to GOP, the use of this code with real video data requires to dynamically build the generator matrix for each GOP. The first step of this process consists in determining the values of $n-k$, $r\_$ and r_P.

Once these variables are set or calculated, the encoder first build a classical systematic MDS generator matrix. For each column corresponding to a redundancy packet, it computes the information data packet that must not be protected by this redundancy repair packet and put to *zero* the coefficient of the corresponding row.

At the receiver side, like for most of erasure codes, the decoding simply performs an inversion of the sub-matrix of

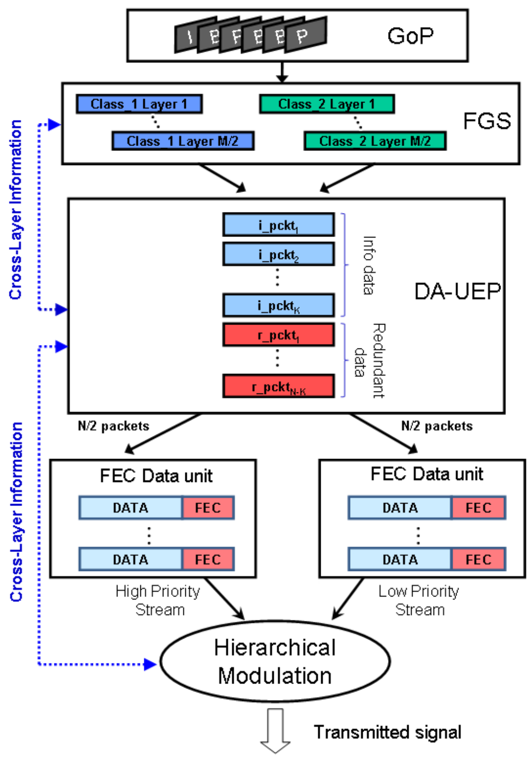

Fig. 2. Cross-layer Unequal Protection Scheme

the generator matrix corresponding to the received packets and multiplies the obtained matrix by the received packets.

The analytical evaluation of the performance of this code can be done by considering this code as several nested MDS codes. This analysis is beyond the scope of this paper.

III. Cross-Layer Architecture

Our objective is to analyse the interest of jointly optimizing unequal protection schemes implemented at different layers. We then integrate all the main reliability mechanisms used at the different layers: hierarchical modulation and error correcting code at the physical layer, erasure code at the transport layer and video FGS coding at the application layer. In order to understand and to evaluate the interactions between these mechanisms, we intentionally choose generic instances of these mechanisms whose the performance can be easily modelled and integrated in an optimization system. Furthermore, we choose to not consider additional layering mechanisms (segmentation/re-assembly, protocol header, etc...), which are specific of each protocol stack and that can modify the evaluation of the set of reliability mechanisms.

Fig. 2 depicts the considered cross-layer architecture. A Group of Pictures (GOP) containing the three frame types (I, P and B) is encoded into different scalable video layers following FGS coding, and considering both SNR and temporal scalability. Two types of layers are differentiated; Class 1 and Class 2. Class 1 layers contain the base layers that must be received for decoding basic video quality, however not necessary meaning that all Class 1 layers are base layers. Then, Class 2 layers are used to improve the video quality. Each type of layer are jointly treated in the DA-UEP coding block, and decomposed in K packets of the same size. Next, the unequal protection scheme is applied in order to create the $N-K$ redundant packets according to the dependencies between packets, their importance and the code rate specified.

Encapsulation protocols are not considered in the Network/Link layers. In order to simplify, the link between DA-UEP and the Modulator is seen as a data unit, which includes an erasure code representing the physical layer forward error correction. The $PER = 1 - P_c$ of the data unit is computed considering randomly error bits, therefore, P_c (i.e. packets correctly received) can be computed using the binomial (6), and simplified using the normal approximation in (7):

$$P_c = \sum_{m=0}^{t} C_m^n p^m (1-p)^{n-m} \tag{6}$$

$$P_c \approx \frac{1}{2}\left(1 + erf\left(\frac{t + 0.5 - np}{\sqrt{2np(1-p)}}\right)\right) \tag{7}$$

where k is the size of info bits, $n-k$ is the number of redundant bits, t is the number of errors that the code is capable of correcting ($t = (n-k)/2$ in case of MDS codes). Note that $n \geq 30$ and $np(1-p) \geq 5$ conditions must be accomplished in order to allow the approximation.

Finally, the two streams ($N/2$ packets go to each stream) are modulated according to the SC QPSK/16QAM scheme, one as High Priority (HP) stream (or basic information) and the other as Low Priority (LP) stream (or enhancement information). We assume Rayleigh channels, future works will contemplate more complex channels, such as Loo and real time series. Note that since we optimize the transmission for different channel distribution features (multipath, line of sight, shadowing, etc), it can be seen not only as a receiver affected by different channel conditions, but also as a group of multicast users, each of one served with a different transmission strategy. The last assumption will be fully explored in future works.

In the Fig. 2, it is also highlighted the cross-layer information used in order to proceed with the joint optimization. In our approach, a global performance parameter (video distorsion) is selected and the intervening protocols in PHY/Transport/APP layers are reviewed in order to identify how their behavior can be improved so as the distorsion is minimized. In particular, this approach would design an efficient information flow among layers from the APP level down to the PHY level. It can be essentially seen as an application-centric approach, where the APP layer optimizes the lower layer parameters. d_1 and d_2 are sent to the PHY layer, the redundancy to be allocated to each video layer is used in the DA-UEP block, and the optimal video layer length distribution is computed at the FGS block of the APP layer.

IV. Cross-Layer Optimization

A. Optimization Problem

The analytical evaluation of the different reliability mechanisms is presented in the last part of this section. To evaluate their interactions, we have expressed the set of these analytical expressions as an optimization problem which was implemented in Matlab. The objective of this implementation is to evaluate the optimal configuration of the parameters of the unequal protection schemes in order to minimize the video distortion (D_t) for a given E_s/N_0 and a fixed Rayleigh channel at the PHY layer. The distorsion depends on the probability of decoding up to the layer i by DA-UEP (f_i), and on the video distorsion achieved ($D(R_i)$) if we decode up to this layer. Thus, D_t can be defined as:

$$D_t = \sum_{i=1}^{M} f_i(k_i, r_i, P_c^{HP}(\lambda), P_c^{LP}(\lambda)) \times D(R_i) \quad (8)$$

where f_i depends on the number of information packets k_i and the redundancy added to each one r_i. It is also affected by the probability of correct packets received of HP and LP streams (P_c^{HP} and P_c^{LP} respectively), which are obtained from (7). At the same time, P_c depends on the BER of each receiver type; (2) and (3), which depend on λ and the channel conditions.

Therefore, considering the variable parameters r_i and λ, together with their defined constraints in HM and DA-UEP sections, the optimization problem can be formulated as follows:

$$\arg\min_{\vec{r},\lambda} \quad D_t(\vec{r}, \lambda) \quad (9)$$

$$s.t. \quad \sum_{i=1}^{M} r_i = r_{max}, \; 0 \le \lambda \le 0.5$$

Since it is a complex problem due to the non-convexity, and thus the solution is complex to find, we propose an iterative solution in order to optimally allocate the needed protection in the HM scheme and at DA-UEP. Moreover, in order to reduce complexity, we fixe the FGS coding (video layers distribution) as explained next.

B. Parameters Definition

Following classical approximations of video distortion, we consider that the video rate distortion curve can be modeled by a decreasing exponential function of bitrate R whose form is $D(R) = S_v \times exp(-\alpha R)$, where S_v is the source variance set to 100 and α is a constant. We consider that the FGS video encoder produces a stream of one base layer and 3 enhancement layers with a maximum rate of $R_{max} = 384$ kbps.

Considering the packets size equal to 500 bytes, the DA-UEP code then protect $K = 96$ data packets containing the video frames by generating $N - K = 32$ redundancy packets. Among the K data packets, $K/4$ packets comes from each layer. The fist two layers and their associated redundancy packets are considered as the high priority stream and the two other layers are the low priority stream.

These two streams are protected (independently) at the physical layer by the same $[n = 2256, k = 1504]$ error-correcting code. The codeword length corresponds to the length of MPEG2-TS packets and allows to recover from 376 errors at most.

The high priority stream is then mapped onto the two most protected bits of the hierarchical modulation and the low priority stream is mapped onto the two least protected bits. Under these assumptions, the variable parameters of the system are the value of $\lambda = d_2/d_1$ characterizing the hierarchical modulation, and the number of redundancy packets allocated to each "layer" of DA-UEP.

An interesting point is that the set of possible parameters includes the cases "HM only" and "unequal erasure protection only". It follows that the resolution of this optimization problem allows to evaluate the interest of jointly optimizing hierarchical modulation and unequal erasure protection compared to non cross-layer solutions.

C. Simulation Results

In this section, we analyze the performance of the cross-layer optimized design and the non-cross-layer designs (only DA-UEP or HM) for different parameters configurations and depending on channel conditions.

Fig. 3 shows our goal by comparing the cross-layer joint optimization with the non-cross-layer optimizations, i.e. HM or DA-UEP independently optimized. In the non-cross-layer scheme, when SC is optimized, DA-UEP is set to equal protection code, and inversely, when DA-UEP is optimized, HM is set ($\lambda = 0.5$) to uniform hierarchical modulation. It can be observed that our cross-layer design obtains better results than the other designs in terms of video distortion, specially for lower values of E_s/N_0, i.e. for worst channel conditions. In this case, the cross-layer solution outperforms DA-UEP up to 50% and SC up to 20%. As expected, when channel conditions are favourable, all optimizations obtain similar values. Note also that HM optimization performs clearly better than the DA-UEP solution, which obtains big distortion for lower E_s/N_0 values.

Fig. 4 will be very useful in order to know the way the optimization is performed and how the parameters evolve depending on channel conditions. In particular, we focus on the redundancy allocated to each video layer as DA-UEP parameter (left axis), and the λ which defines the SC scheme (right axis). We can observe that, when users are affected by bad channel conditions $\lambda = 0$, which means that only QPSK modulation is transmitted in order to avoid increasing the PER. At higher layers, the redundancy allocated to the corresponding 16QAM data is simply set to zeros ($r_3 = r_4 = 0$) and the whole redundancy is allocated to the first two layers of the DA-UEP codes (r_1 and r_2). In this state, the DA-UEP favors the first layer over the second one ($r_1 > r_2$) when the channel is too bad. This state holds until E_s/N_0 = 22 dB, then at E_s/N_0 = 23 dB the channel is better enough for DA-UEP to protect both first layers equivalently ($r_2 > r_1$).

On the other hand, for values greater than 23 dB, the behavior changes, and higher values of λ are optimally allocated, which makes the overall throughput increase due to the hierarchical transmission with QPSK and 16QAM users. At DA-UEP, the code provides unequal protection for both layers of HM schemes ($r_1 > r_2$ and $r_3 > r_4$). As the channel

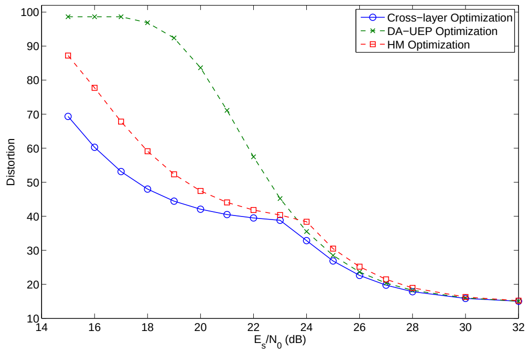

Fig. 3. Comparison in terms of Video Distortion between the cross-layer optimization and the independent non-cross-layer optimizations.

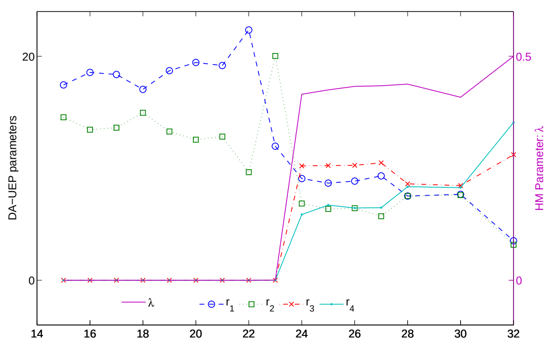

Fig. 4. Evolution of DA-UEP (redundancy allocated to each video layer, left axis) and HM (λ, right axis) parameters for the cross-layer optimisation.

gets better, both SC schemes and DA-UEP tends to equally protect data $\lambda = 0.5$ and $r_1 \approx r_2 << r_3 << r_4$. Therefore, all video layers are protected in the optimal way, i.e. in order to obtain the best video quality distorsion.

V. Conclusion

In this paper, we present a multi-layer protection scheme based on a Application/Transport/PHY joint layer design by taking advantage of the exchange of cross-layer information. The chosen techniques, both allowing users diversity depending on channel conditions, are FGS/DA-UEP at the transport layer, and Hierarchical Modulation at the physical layer. FGS/DA-UEP achieves high efficiency by optimizing the layers length and the redundancy added to each one, which is allocated depending on the dependencies between frames at data level. On the other hand, our physical layer takes profit of the Hierarchical Modulation scheme, which achieves highest overall throughput than other solutions and it is modeled according to the distances between constellation symbols (d_1 and d_2).

The results show that the cross-layer design outperforms the independent non-cross-layer solution in up to 50% for DA-UEP, and up to 20% in HM, for the range of channel values studied herein. Moreover, we have shown how the parameters adapts in order to find the optimal solution for each channel state.

Future work includes the increase of system model complexity by using different Rice/Loo channel distribution, real video coding, and studied in terms of PSNR/MOS. Moreover, since both techniques allow for users diversity with different channel conditions, the multicast scenario will be studied in depth, as in [3] but considering the joint cross-layer design. In particular, the case where different types of QoS will be served to different groups of users by using the layers/stream differentiation at PHY and APP level.

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