ROBUST AND EXTREME UNEQUAL ERROR PROTECTION SCHEME FOR THE TRANSMISSION OF SCALABLE DATA OVER OFDM SYSTEMS

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ABSTRACT

Wireless applications are subject to the *end-to-end Quality of Service* (QoS) requirements. This paper presents a new resources allocation algorithm that allows to transmit scalable multimedia data over a frequency selective channel with partial channel knowledge. The available resources are subject to payload and QoS constraints and the algorithm aims at maximizing the transmission robustness to channel estimation errors. The impact of this technique is evaluated for a MPEG-4 audio application.

***Index Terms*—** Unequal error protection, Resources allocation, OFDM, Scalable data, Joint source-channel coding.

1. INTRODUCTION

Multimedia transmission systems convey data with heterogeneous information: media nature (as audio or video), coded features (such as intra images, movement vectors for video). This information heterogeneity allows to design such systems whose efficiency is related to the Quality of Service (QoS). QoS reflects the distortion caused by the source coder and the channel environment (through a subjective measurement criterion) and is given by the considered reception device.

With scalable source coders, data are sorted in hierarchized classes of importance or *layers* with different sensitivities to channel transmission errors. This data structure favors the use of *Unequal Error Protection* (UEP) schemes, that have already proved their efficiency on system QoS. These schemes adapt the protection of the transmitted bits according to their importance degree and the channel transmission conditions, working on the resources offered by the transmission scheme (coding rate, modulation). Since most source decoders lack of robustness to erroneous bits, system performance is improved as soon as the allocation strategy includes resources offered by the source encoding stage, yielding to the joint source-channel coding techniques. In this field, most strategies [1] base the allocation procedure on the minimization of the distortion introduced by the source and the channel coding on the received data. It does not match with our application scenario[1], where the required QoS belongs to system contraints. Thus, we have proposed an *extreme UEP* scheme [2] suitable for scalable data transmission: it is designed on the key idea of transmitting only the layers that are enough protected to achieve the QoS requirements. Thus, using a simple expression of the QoS as targeted Bit Error Rate (BER) per class, the source and channel resources are jointly selected by maximizing the number of transmitted source data and minimizing the channel payload.

Most State-Of-The-Art strategies require to inform the transmitter on the *Channel State Information (CSI)*. The channel state is estimated at the receiver and is sent to the transmitter through a feedback channel. Allocation methods share the assumption of a perfect CSI knowledge at the transmitter, that wireless applications do not meet. The channel estimation error must therefore be taken into account in the resources allocation procedure to satisfy the system QoS requirements. In this joint source-channel context, we hence propose a new extreme UEP scheme that maximizes the transmission robustness to estimation errors of channel parameters.

The rest of the paper is organized as follows. Section 2 describes the communication system, while the section 3 recalls the extreme UEP algorithm in the perfect CSI case [2]. Section 4 details the proposed robust UEP scheme in partial CSI case. Section 5 illustrates the efficiency of our method through a MPEG-4 audio application. Finally, Section 6 concludes on the contribution of our algorithm.

2. SYSTEM DESCRIPTION

The reference transmission system is presented in figure 1 and is detailed in the following subsections.

2.1. Source coding parameters

Thanks to the scalable encoding process, multimedia data are structured into frames or Transmission Units (TU). These frames are split into I_{max} layers: one base layer and $I_{max}-1$ enhancement layers, denoted by $\{\mathcal{L}\}_{i\in[1,I_{max}]}$, with decreasing importance degrees. The length of the i-th layer (in bits) is equal to C_i and the total frame length is $N=\sum_{i=1}^{I_{max}} C_i$. The importance degree of each layer features [3] both its weight on the source distortion D_s (due to source encoding) and its sensitivity to channel transmission errors influencing the channel distortion D_c. The source and channel distortion is therefore directly related to the number of emitted layers, denoted by I, or equivalently a source rate, defined as:

$$\mathbb{R}_s(I)=\sum_{i=1}^{I} C_i. \tag{1}$$

Following [4], the error sensitivity of each layer i is featured by a bit error probability value, denoted by B_i. This value is de-

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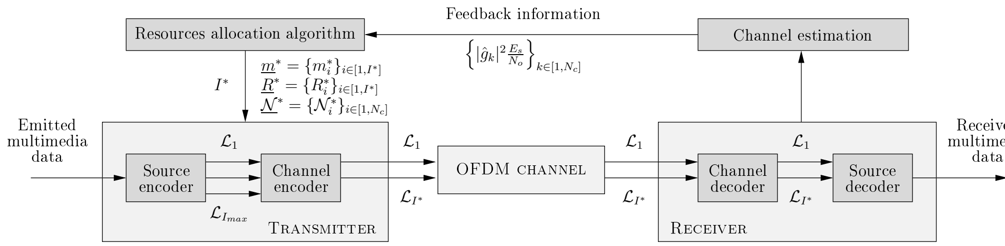

Fig. 1. Transmission scheme piloted by the extreme UEP algorithm

fined according to some perceptual quality criterion so that, when the BER affecting the transmission of the i-th layer is lower than B_i, the source decoding of this layer has no (or few) influence on D_c. Therefore, ensuring the QoS consists of guaranteeing the BER affecting each layer i, denoted by BER_i, to be lower than B_i, yielding the I_{max} QoS requirements:

$$\forall i \in [1, I_{max}], BER_i \leq B_i \tag{2}$$

2.2. Transmission model

At the transmitter, source data are first encoded with a channel coding chosen among rate-compatible channel encoder [5]. In this paper, we use *Rate Compatible Punctured Convolutional* (RCPC) codes, but it could easily be extended to any other rate-compatible encoding process (such as turbo codes). Thanks to the puncturing process of a mother convolutional code (with rate R_m) with a puncturing period P, a set $\mathcal{R}$ of $(P-1)/R_m$ coding rates R_l is available. The coded data are then mapped with one of the available signalling constellations $\mathcal{M}$: BPSK or 2^{2m}-QAM with constant symbol energy E_s. The order m denotes the number of bits per symbol and refer to a specific modulation choice (assuming $m = 1$ is BPSK). A block interleaver is finally used to disperse burst errors.

When the length of the cyclic prefix is longer than the coherence time, the frequency selective channel is turned into scalar channel gains $\{g_k\}_{k\in[1,N_c]}$ on the N_c different OFDM carriers: the Signal-to-Noise-Ratio (SNR) of the k-th carrier is $SNR_k = |g_k|^2 \frac{E_s}{N_o}$, with N_o the noise variance. Assuming that the channel varies slowly, we define T as the number of periods while channel time response is constant. The maximum symbol load per coded TU, S_{max}, is chosen equal to TN_c and is defined at the physical layer. It refers to the physical payload.

At the receiver, we assume the OFDM system is synchronization error free. After Zero-Forcing equalization, a soft output maximum *a posteriori* demapper is used to compute soft decision values, applied as input of a classical Viterbi decoder. A channel estimation module is linked with the transmitter through a feed-back channel and informs it about the estimated channel conditions (i.e. $S\hat{N}R_k = \left\{|\hat{g}_k|^2 \frac{E_s}{N_o}\right\}_{k\in[1,N_c]}$ with $\hat{g}_k$ the estimated gain of the k-th OFDM carrier). The bitstream header transmission is assumed to be error-free.

3. EXTREME UEP WITH PERFECT CSI

Regarding the system characteristics, the resources allocation procedure aims at choosing the adapted system parameters that ensures the QoS constraints. These parameters are: the number of transmitted layers I^* and, for each transmitted layer $\mathcal{L}_i$, the modulation order m_i^*, the coding rate R_i^* and the OFDM carriers, defined by the index subset $\mathcal{N}_i^*$ (with N_i^* elements), dedicated to its transmission. Furthermore, the QoS and payload constraints are stated by the $\{B_i\}_{i\in[1,I_{max}]}$ bounds and the symbol rate S_{max}.

3.1. Problem formulation

As stated in [2] for a frequency selective channel with perfect channel knowledge, the transmission parameters are optimally chosen among the set of possibilities $\mathcal{P}$[2] in order to convey as many layers as possible under payload and QoS constraints. This allocation strategy is related to an optimization problem, that consists of maximizing the source rate $\mathbb{R}_s$ under the previous constraints focusing on the solution that minimizes the symbol payload S_{TU}. Taking advantage of the channel frequency selectivity, the carriers allocation policy assigns the best carriers (in the sense of the highest channel gains $\{g_k\}_{k\in[1,N_c]}$) to the layers with the highest error sensitivity degrees. Moreover, the BER affecting the i-th layer transmission depends on the SNRs of the carriers $\mathcal{N}_i$ involved in its transmission. Thus, the QoS constraints given by equation (2) can easily be overestimated considering the carrier $n_{min}(i)$ with the lowest channel gain among $\mathcal{N}_i$.

The mathematical formulation of this problem can therefore be given by:

$$\begin{cases} I^* = \arg \max\limits_{I\in[1,I_{max}]} \mathbb{R}_s(I) \\ (\underline{m}^*, \underline{R}^*, \underline{\mathcal{N}}^*) = \arg \min\limits_{(\underline{m},\underline{R},\underline{\mathcal{N}})\in\mathcal{P}} S_{TU} \\ s.t. \left| \begin{array}{l} \forall i \in [1, I], \text{BER}(m_i, R_i, SNR_{n_{min}(i)}) \leq B_i, \\ \forall i \in [1, I], n_{min}(i) = \arg \min\limits_{k\in\mathcal{N}_i} |g_k|^2 \\ \\ S_{TU} = \sum\limits_{i=1}^{I} S_i(m_i, R_i) \leq S_{max} \end{array} \right. \end{cases} \tag{3}$$

where S_i denotes the number of symbols transmitted within the coded $\mathcal{L}_i$, $SNR_{n_{min(i)}}$ the SNR value of the OFDM carrier with index $n_{min(i)}$ and $\underline{m} = \{m_i\}_{i\in[1,I]}$, $\underline{R} = \{R_i\}_{i\in[1,I]}$, $\underline{\mathcal{N}} = \{\mathcal{N}_i\}_{i\in[1,I]}$ are vectorial representations of the allocated transmission parameters.

3.2. Extreme UEP algorithm

The extreme UEP algorithm designed to solve this optimization problem proceeds in an iterative way, layer by layer, starting with the most important one. For each selected layer i, the appropriate transmission parameters $(m_i, R_i, \mathcal{N}_i)$ are derived, taking the SNR of the lowest carrier (involved in the layer transmission) into account to ensure the QoS constraint (2) and keeping only the solution that minimizes S_i. Once a layer is processed, the payload S_{TU} is updated and the next layer is considered, while the S_{max} or I_{max} constraints are not reached.

[2]with $\mathcal{P} = \left\{\{(R_i, m_i, \mathcal{N}_i)\}_{i\in[1,I^*]} / R_i \in \mathcal{R}, m_i \in \mathcal{M}, \mathcal{N}_i \in [1, N_c]\right\}$

4. EXTREME UEP WITH PARTIAL CSI

CSI contains errors with multiple origins: bad estimation of the channel due to noise at the receiver, noisy feedback channel (quantization noise), strong and fast time variations of the channel. These errors corrupt the SNR_k values delivered to the allocation resources procedure. Minimizing the payload S_{TU}, as proposed on the previous algorithm, may not ensure the QoS of the transmitted layers. It has to be replaced by a robustness criterion: a SNR margin.

4.1. Robustness criterion definition

We propose to improve the robustness of the transmitted data to channel estimation errors, while keeping the same system contraints, that is the BER bounds and the maximum payload. A relevant robustness criterion is a SNR margin on the channel estimation error, that reflects the maximum admissible overestimation on SNR that the system can endured without performance degradation.

Indeed, considering the resources configuration $(m_i, R_i, \mathcal{N}_i)$ of the i-th layer, the QoS constraint given by equation (2) can be turned in terms of SNR values as follows:

$$\Delta SNR_i(m_i, R_i, \mathcal{N}_i) = SNR_{n_{min}(i)} - SNR_{B_i} \geq 0. \quad (4)$$

where SNR_{B_i} denotes the required SNR value that guarantees a BER equal to B_i and $\Delta SNR_i(m_i, R_i, \mathcal{N}_i)$ is the SNR overestimation margin for the i-th layer. The higher the margin is, the better the BER and thus the robustness. Finally, maximizing the SNR margins of the entire transmitted layers can be achieved as soon as the lowest one is maximized, that is:

$$\Delta SNR_{min}(\underline{m}, \underline{R}, \underline{\mathcal{N}}) = \min_{i \in [1, I^*]} \Delta SNR_i(m_i, R_i, \mathcal{N}_i). \quad (5)$$

4.2. The robust extreme UEP scheme

Using the robustness criterion, the optimization problem becomes:

$$\begin{cases} I^* = \arg \max\limits_{I \in [1, I_{max}]} \mathbb{R}_s(I) \\ (\underline{m}^*, \underline{R}^*, \underline{\mathcal{N}}^*) = \arg \max\limits_{(\underline{m}, \underline{R}, \underline{\mathcal{N}}) \in \mathcal{P}} \Delta SNR_{min}(\underline{m}, \underline{R}, \underline{\mathcal{N}}) \\ \Delta SNR_{min}(\underline{m}, \underline{R}, \underline{\mathcal{N}}) \geq 0 \\ S_{TU} = \sum\limits_{i=1}^{I} S_i(m_i, R_i) \leq S_{max} \end{cases} \quad (6)$$

We propose to solve this problem using the same iterative principle than the previous extreme UEP algorithm. Based on the waterfilling procedure depicted in figure 2(a), the transmission parameters allocation achieve an optimal robustness level expressed through the robustness margins , as follows:

• Initialization: The algorithm described in section 3.2 is processed to derive the initialization parameters $(I^*, \underline{m}^*, \underline{R}^*, \underline{\mathcal{N}}^*)$. Then, the initial robustness margins ΔSNR_i of the I^* transmitted layers are computed.

• Iteration: Considering the layer with the smallest robustness margin ΔSNR_{min} (the 2^{nd} one in figure 2(b) at iteration 1), this margin is increased by overprotecting this layer, while the S_{max} constraint is not reached and while this layer still has the smallest robustness margin. If the last condition is reached, robustness margin ΔSNR_{min}, transmission parameters and current payload S_{TU} are updated. The next iteration is then performed with the "new" most sensitive layer in terms of robustness margin (the 4^{th} in figure 2(b) at iteration 2).

• Stopping condition: The algorithm proceeds the same task until 1) looping every possible resources combinations for the I^* layers

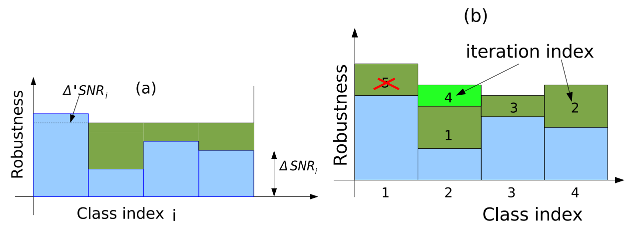

Fig. 2. Iterative resources allocation over the most sensitive layers

without involving resources configuration changes or 2) reaching the S_{max} constraint (as achieved figure 2(b) at iteration 5).

5. APPLICATION TO MPEG-4 SPEECH DATA

An application of the proposed algorithm to the transmission of scalable speech data is at stake to evaluate the algorithm performance.

5.1. Test plan

5.1.1. Transmission system parameters

Among the several source coding tools of the MPEG-4 standard [6], we focus on the CELP encoder with the MultiPulse Excitation and the Bit-Rate Scalability tools. This coder represents a speech signal sampled at 8 kHz by a scalable bitstream structured in 4 layers with length: $C_1 = 120$, $C_{2,3,4} = 40$. We assume that the QoS expected by our application can be described by the following BER upper bounds: $B_1 = 3.10^{-3}$, $B_2 = 4,6.10^{-3}$, $B_3 = 8.10^{-3}$, $B_4 = 9.10^{-3}$.

RCPC codes are generated from a mother convolutional with rate $\frac{1}{3}$, enumerator polynoms $G_1 = [133]_8, G_2 = [145]_8$ and $G_3 = [175]_8$, and a puncturing period equal to 8. The modulation schemes choice are limited to BPSK, QPSK, 16-QAM and 64-QAM.

The OFDM parameters are the following: the number of subchannels in an OFDM symbol is fixed to $N_c = 120$, the OFDM coherence time is $T = 3$, yielding a maximum symbol load per coded TU $S_{max} = TN_c = 360$. Moreover, the symbol energy E_s is fixed to 1.

5.1.2. Channel model

The frequency selective channel is generated as follows: denoting by Δ the channel dynamic and $\overline{SNR}$ the mean SNR, the SNR values $|g_k|^2 E_s/N_o$ of each carrier k are computed in order to follow a linear decrease law (in dB) around $\overline{SNR}$ so that:

$$10 \log_{10}\left(|g_k|^2 \frac{E_s}{N_o}\right) = 10 \log_{10}\left(\overline{SNR}\right) + \left(\frac{\Delta}{2N_c} - k + 1\right) \quad (7)$$

5.1.3. Channel estimation error model

We suppose that the channel estimation stage delivers an erroneous estimation of the channel gains $\{\hat{g}_k\}_{k \in [1, N_c]}$ based on N_s pilot symbols. We modeled this estimation error with additive Gaussian random variables $\{\varepsilon_k\}_{k \in [1, N_c]}$ so that $\forall k \in [1, N_c], \hat{g}_k = g_k + \varepsilon_k$. Since the estimation error only depends on the additive, white, centered and complex Gaussian noise (with variance N_o) that corrupts the transmitted multimedia signal, the mean and variance of the random variables $\{\varepsilon(k)\}_{k \in [1, N_c]}$ are given with respect to N_o and N_s by: $E[\varepsilon_k] = 0$ and $Var[\varepsilon_k] = N_o/N_s$. Hence, for each carrier k,

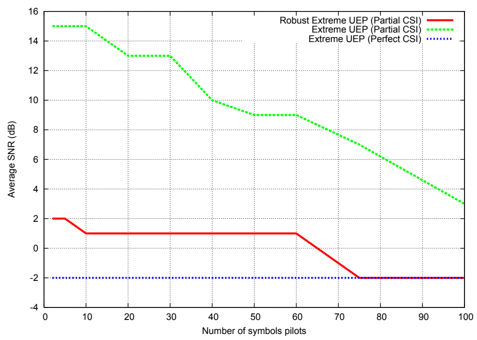

Fig. 3. Robustness performance for different transmission strategies in Rayleigh channel case

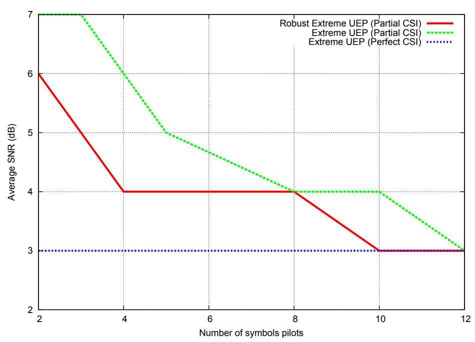

Fig. 4. Robustness performance for different transmission strategies in a frequency selective channel case with a dynamic of 30 dB

the $S\hat{N}R_k$ value used by the allocation procedure is affected by an error ε_{SNR} that follows a Gamma rule with parameter $l = 1$ and $\theta = \frac{N_o}{N_s}$ (since $E(\varepsilon_{SNR}) = \frac{1}{N_s}$). As a consequence, the higher N_s is, the lower is the error on $S\hat{N}R_k$.

5.1.4. Robustness evaluation protocol

The system end-to-end QoS is evaluated with an objective measurement, namely the *Mean Opinion Score* (MOS), of the distorsion between the received speech signal and the emitted one. Using the *Perceptual Evaluation of Speech Quality* [7] software, this MOS is delivered in the range $[0, 4]$, from strong distortions to unperceptible ones. To evaluate the Robust Extreme UEP (RE-UEP) algorithm efficiency in terms of robustness to channel error estimation, we measure the minimum channel mean SNR, denoted by $\overline{SNR}_{min}$, required to reach an expected QoS Q (or equivalently an excepted value of the MOS). We choose to impose a MOS equal to 3, meaning an "*audible but not annoying distortion*". Simulations are performed on a 10s duration signal and results are averaged over 50 transmissions. Finally, the performance of our scheme will be compared to the Extreme UEP (E-UEP) algorithm, described section 3.2.

5.2. Experimental results

Figures 3 and 4 depict the evolution of the minimum admissible mean SNR ($\overline{SNR}_{min}$) that guarantees a MOS equal to 3 with respect to the number of pilot symbols N_s for a Rayleigh and a frequency selective channel. The $\overline{SNR}_{min}$ obtained when the channel state is perfectly known is also indicated for comparison purpose.

As expected, the E-UEP performance obtained in the perfect CSI case decreases as soon as the channel is badly estimated: for the Rayleigh channel drawn figure 3, the $\overline{SNR}_{min}$ increases from -2 to 15 dB for $N_s \leq 10$. This degradation is weaker for an OFDM frequency selective channel (figure 4), since the $\overline{SNR}_{min}$ increases from 3 to 7 dB when $N_s = 3$.

RE-UEP and E-UEP can be declared as robust to channel estimation errors when their performance achieve the same $\overline{SNR}_{min}$ than the one of E-UEP in perfect CSI case, with the same number of pilot symbols N_s. The lowest value of N_s for which this configuration is obtained is called the *robustness operating point*. In partial CSI case, the RE-UEP algorithm outperforms the other strategy. For Rayleight channel, the RE-UEP robustness operating point is reached at $\overline{SNR}_{min} = -2$ dB for $N_s = 75$, while E-UEP needs more than 100 pilots. This improvement is effective but smaller for OFDM channel: E-UEP reaches the robustness operating point for $N_s = 12$, while the RE-UEP only requires $N_s = 10$. This can be explain by the RE-UEP behaviour to channel dynamic increase: given a fixed mean SNR, the overprotection policy inherent to the algorithm can not warranty a robustness margin improvment: the overprotected transmission of the i-th layer is conveyed by OFDM carriers, whose SNRs become as smaller as the dynamic increases. And, since the QoS is related to the carrier with the weakest SNR, the BER bound is no more satisfied, which occurs much quickly when the dynamic increases. Thus, the channel distribution influences the robustness margin improvement.

6. CONCLUSION

In this paper, we described a new robust algorithm that performs Extreme UEP for the transmission of the scalable data without increasing the number of used resources. We showed the efficiency (good performance), the flexibility (to frequency selective channel) and the robustness (in partial CSI) of our transmission scheme.

7. REFERENCES

[1] H. Zheng and K. Ray Liu, "Robust image and video transmission over spectrally shaped channels using mutlicarrier modulation," *IEEE Trans. on Multimedia*, vol. 1, no. 1, pp. 88–103, 1999.

[2] H. Houas, C. Baras, and I. Fijalkow, "A new transmission strategy for scalable multimedia data on ofdm systems," in *EUSIPCO*, Poznan, Poland, september 2007.

[3] G. Cheung and A. Zakhor, "Bit allocation for joint source/channel coding of scalable video," *IEEE Trans. on Image Processing*, vol. 9, no. 3, pp. 340–356, March 2000.

[4] D. Dardari, M. G. Martini, M. Mazzotti, and M. Chiani, "Layered video transmission on adaptive OFDM wireless systems," *EURASIP Journal on Applied Signal Processing*, vol. 4, no. 10, pp. 1557–1567, 2004.

[5] J. Hagenauer, "Rate-compatible punctured convolutional codes and their application," *IEEE Trans. on Communications*, vol. 36, no. 4, pp. 389–400, April 1988.

[6] F. Pereira and T. Ebrahimi, *The MPEG-4 book*. IMSC Press Multimedia Series, Prentice Hall PTR, may 2002.

[7] IUT-T Recommendation P. 862, *Perceptual evaluation of speech quality (PESQ): An objective method for end-to-end speech quality assessment of narrow-band telephone networks and speech codecs*, 2001.