

Quantitative perceptual comparison of variable bit rate over constant bit rate encoding scheme for MPEG-4 video

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Abstract. *Between the two main schemes of digital video coding, the variable bit rate (VBR) encoding scheme is generally considered better in terms of efficiency and encoding quality in comparison to the constant bit rate (CBR), because it retains the same quantization parameters for the whole encoding procedure (unconstrained VBR), without altering them according to a specific adaptive rate algorithm. Toward this generally accepted statement, we present a quantitative comparison to the perceptual efficiency of the VBR over the CBR for the Moving Picture Expert Group-4 (MPEG-4) ASP CIF and QCIF encoding sequences, showing that the VBR does not outperform significantly the corresponding CBR encoding quality, since the deduced perceptual advantage/ratio of the VBR over the CBR for the CIF is approximately 4–5% and is constant for all the encoding bit rates greater than 200 kbps, while for the QCIF case the relative ratio drops to approximately 2.5%. © 2007 SPIE and IS&T.*

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1 Introduction

From the advent of video coding, two main encoding schemes were proposed and are still in use: the constant bit rate (CBR) and the variable bit rate (VBR). The VBR mode retains the same quantization parameters for all the encoding process in contrast to the CBR mode, which adapts the

quantization parameters dynamically according to a sophisticated rate algorithm in proportion to the spatial and temporal activity of the encoding video signal.

Today, the choice of VBR mode for video services over communication networks generally prevails over CBR mode due to a number of advantages such as¹

- Better video quality for the same average bit rate without the complexity of an adaptive rate algorithm
- Shorter transmission delay since the buffer size in the encoder side can be reduced without encountering an equivalent delay in the network
- Increased call-carrying capacity due to the fact that the bandwidth per call for VBR video may be lower than for equivalent quality of CBR source.
- Better exploitation of the available capacity of the transmission channel by the statistical multiplexing of VBR streams in comparison to CBR streams.

Thus, it is generally supported that more efficient network utilization can be achieved by choosing VBR encoding mode.

However, except for the pure network-based selection of the encoding mode (i.e., CBR or VBR), the fact that the perceived quality degradation is caused by the digital video compression process has raised the issue of the user satisfaction (i.e., perceived video quality level or perceived quality of service)² in correlation with the selected encoding parameters.

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Among the various encoding parameters that play a significant role in the deduced perceived quality of service (PQoS) (e.g., bit rate, spatial and temporal resolution), the selection of VBR or CBR encoding mode is critical for the final perceptual outcome. Although a lot of research has been focused on developing techniques and methods for estimating the video quality of a compressed/encoded video signal,³⁻¹⁶ the issue of studying quantitatively the perceptual efficiency of the VBR over CBR mode has not yet been performed. The engineers generally select the VBR over the CBR due to the aforementioned theoretical advantages of the first, usually simply using the PSNR metric for measuring its encoding efficiency, without taking into consideration the actual perceptual impact of the VBR over the CBR.

This paper presents a quantitative study on the perceptual effectiveness of the VBR over the CBR in correlation to the encoding bit rate, considering that the encoding parameters (e.g., spatial and temporal resolution, encoding scheme, GOP pattern, etc.) remain constant. Toward this end, we provide results depicting the actual perceived efficiency of VBR/CBR modes and not only the engineering effectiveness of each one, which may be measurable by simple error-based metrics but not actually perceived by the human visual system.

The rest of the paper is organized as follows: Section 2 discusses the various video quality metrics and methods that have been proposed in the literature and explains the research method, which this paper has followed. Section 3 presents the experimental results of VBR/CBR video quality evaluation, quantifying the perceptual efficiency of the VBR over the CBR for both CIF and QCIF resolution. Finally, Section 4 concludes the paper, discussing the outcomes of this work.

2 Video Quality Metrics

The evaluation of the video quality is a matter of objective and subjective procedures, which take place after the encoding process (post-encoding evaluation). Subjective quality evaluation processes of video streams require a large amount of human resources, establishing it as a time-consuming process (e.g., large audiences evaluating video/audio sequences).³⁻⁵ Objective evaluation methods, on the other hand, can provide PQoS evaluation results faster but require large amount of machine resources and sophisticated apparatus configurations.

The majority of the existing objective methods in the literature requires the undistorted source video sequence as a reference entity in the quality evaluation process; due to this, these methods are characterized as full reference (FR).⁶⁻¹³ Basically, these methods are based on an error sensitivity framework between the uncompressed and the encoded video signal, while frame-by-frame comparison is performed. When the original undistorted/uncompressed video signal is not required for the video quality evaluation process, then the objective method is characterized as non-reference (NR).^{14,15} Recently, some works have been published that exploit some already proposed FR or NR metrics in order to predict the final perceived quality of a specific encoded sequence at a pre-encoding stage.¹⁶⁻¹⁸

For the needs of this paper, in order to quantify the perceptual difference between the CBR and VBR encoding

efficiency, the use of objective instead of subjective procedures was preferred. Since the perceptual difference between the two encoding schemes is expected to be rather small, the subjective assessments could not be able to provide a reliable result due to the relatively high statistical error,²² which will encompass the corresponding evaluation. Keeping this restriction in mind, we decided to use four objective FR metrics in the evaluation procedure: the FR peak signal-to-noise ratio (PSNR), the FR structural similarity (SSIM),^{12,13} the FR digital video quality (DVQ),⁸ and the FR delta metric.¹⁹ These four efficient FR objective metrics will provide accurate and specific results for the perceptual efficiency of the encoding schemes, without introducing significant statistical errors, which may cause error propagation in the processing, therefore eliminating the accuracy of our results. Information about the correlation of these objective metrics to subjective evaluation procedures can be found in Ref. 21 (for more detailed description, please see the relative references). For completeness of the paper, we briefly hereby describe each metric.

2.1 PSNR

The peak signal-to-noise ratio is one of the more tangible parameters used to measure video quality. The specific metric is provided during the compression process by the encoder and is defined as follows:

$$\text{PSNR} = 10 \log_{10} \frac{L^2}{\text{MSE}},$$

where L denotes the dynamic pixel value (i.e., equal to 255 for an 8-bit/pixel monotonic signal), and the mean-square error is defined as

$$\text{MSE} = \frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2,$$

where N denotes the number of pixels of the selected spatial resolution and x_i/y_i the i th pixel value in the original/encoded frame.

2.2 SSIM

SSIM is a novel FR metric for measuring the structural similarity between two image sequences, exploiting the general principle that the main function of the human visual system is the extraction of structural information from the viewing field. If x and y are two video frames, then the SSIM is defined as

$$\text{SSIM}(x, y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)},$$

where μ_x and μ_y are the mean of x and y , σ_x , σ_y , and σ_{xy} are the variances of x , y and the covariance of x and y , respectively. The constants C_1 and C_2 are defined as

$$C_1 = (K_1L)^2 \quad C_2 = (K_2L)^2,$$

where L is the dynamic pixel range and $K_1=0.01$ and $K_2=0.03$, respectively.^{12,13}

2.3 Delta

Delta is a gray-scale measure that calculates the distances in either discrete or continuous space. The distance between two picture functions can be defined as the mathematical distance between the volumes beneath the two functions. Considering that f and g are two images defined in the pixel raster X , featuring the same gray levels, with Γ_f and Γ_g being the subgraphs of f and g , respectively,¹⁹ then the Delta metric Δ_g is defined as

$$\Delta_g(\Gamma_f, \Gamma_g) = \left[\frac{1}{n(X)n(Y)} \sum_{x \in X} \sum_{y \in Y} |d((x,y), \Gamma_f) - d((x,y), \Gamma_g)|^p \right]^{1/p} \quad \text{for } 1 \leq p \leq \infty.$$

2.4 DVQ

This metric is based on the discrete cosine transform. It incorporates aspects of early visual processing, including light adaptation, luminance and chromatic channels, spatiotemporal filtering, spatial frequency channels, contrast masking, and probability summation.⁸ DVQ uses the discrete cosine transform (DCT) in order to perform decomposition of the original data into spatial channels. This provides a powerful advantage toward the implementation of this metric, since efficient hardware and software are available for this transformation and because in many applications the transform may have already been done as part of the compression process.

The use of these four FR objective quality metrics for the video quality evaluation process ensures the accuracy of the deduced results, because possible limitations of each metric on the deduced measurements are generally eliminated by the use of the rest metrics.

3 Video Quality Evaluation

For the experiments in this paper, the ISO MPEG-4 codec implementation developed by the Ducas Corporation was used. The Ducas Corporation is an official member of the MPEG Industry Forum and a supporter of the AVC Alliance, denoting the close relationship of this implementation to the standard. Regarding the selection of the profile (the profile in MPEG-4 is a set of tools that define a conformance point), although the presented experimental results could be derived for any MPEG-4 visual profile (Simple, Core, Main, Advanced Simple Profile), the Advanced Simple Profile was selected because it is the most widely used profile in MPEG-4 commercial applications (e.g., mobile phones, cameras, codec software/hardware, etc.), while the other profiles are mainly restricted to the MPEG-4 reference encoder implementation. Moreover, the Simple, Core, and Main Profiles are subsets of the Advanced Simple Profile, which means that any video stream that complies to the Simple, Core, and Main Profiles also complies with the Advanced Simple Profile. More specifically, the ASP specifications fit well with the selected spatial resolution values (i.e., CIF and QCIF), supporting all the main features of MPEG-4, such as the Basic Visual Tools, Error resilience, short header, B-VOP, Method 1/2 quanti-

zation, and 1/2 Pel pixel motion compensation. Thus, the selection of ASP for our experiments is in many ways beneficial and interesting.

For the evaluation process of the video quality, five reference video clips were used (i.e., Suzie, Cactus, Flower Garden, Table-Tennis, and Mobile & Calendar), which represent a wide range of spatial and temporal activity level. These video clips were encoded from their original uncompressed format to ISO MPEG-4 CIF resolution Advanced Simple Profile at various bit rates (i.e., 100, 150, 200, 250, 300, 400, 500 kbps), using both the CBR and VBR encoding modes.

At the encoder, the encoding parameters were selected as follows: the MPEG GOV Structure was set with Key Frame Period 100 frames and B frame period 2 frames. The trade-off between compression quality efficiency and the encoding speed was set at "High Quality." Regarding the CBR mode, a VBV buffer implementation was used with buffer size equal to 1 second.

From each test sequence, 20 randomly selected decoded frames were extracted and used for the video quality evaluation/comparison between the VBR and CBR modes for all the encoding bit rates (i.e., 100–500 kbps). The selected decoded frames belonged to either the I, P, or B frame type, ensuring by this way the testing of both intra- and intercoding efficiency.

In order to provide a normalization of the video quality evaluation scale of each metric, for the five video test signals the ratio of the perceived quality level of the VBR (PQVBR) over the perceived quality level of the CBR (PQCBR) is calculated for all the testing encoding bit rates. Thus, for each quality metric, the PQVBR/PQCBR ratio is derived for the whole test signal set, which is normalized and independent of the quality scale of each metric. Also, for those metrics (i.e., VQM and delta) that do not follow an ascending scale (i.e., the deduced quality value becomes lower for better encoding quality), the inverse values have been used in the calculation of PQVBR/PQCBR ratio in order to provide common results with the rest metrics, where the higher values correspond to better encoding quality, and vice versa.

For each x_k of the deduced PQVBR/PQCBR ratios at any m th encoding bit rate for all the i test sequences, the

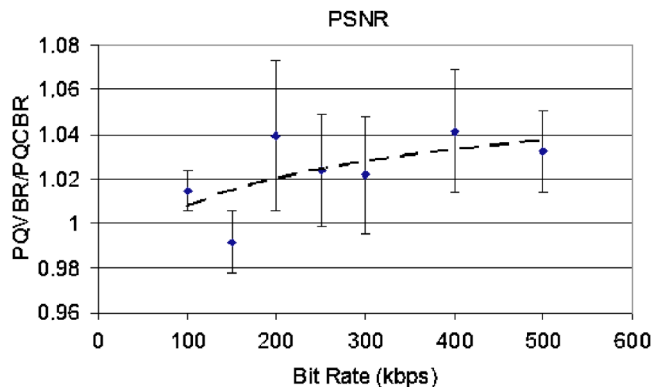


Fig. 1 The PQVBR/PQCBR ratio of the SNR metric for the whole test-signal set.

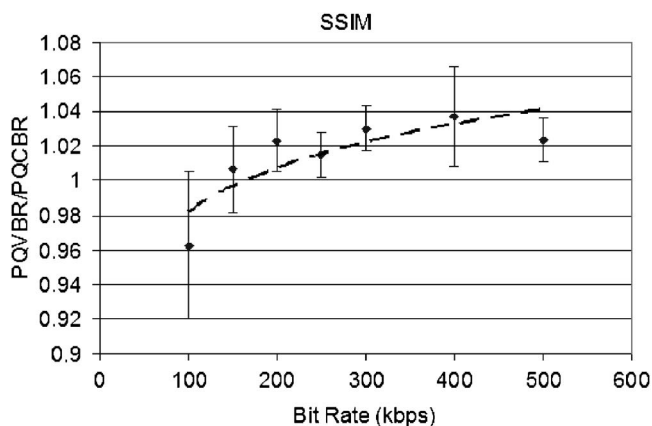


Fig. 2 The PQVBR/PQCBR ratio of the SSIM metric for the whole test-signal set.

corresponding mean value and the standard deviation of each k objective metric are then derived according to the following equations:

$$\bar{x}_k = \frac{1}{N} \sum_{i=1}^N x_i, \quad \delta x_k = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N(N-1)}}.$$

Thus, each k objective metric provides a single measurement for the PQVBR/PQCBR ratio for all the test sequences at any given m th bit rate, of the form $x_k = \bar{x}_k \pm \delta x_k$. Moreover, in order to retain the accuracy of the deduced results, the Chauvenet criterion was also applied on the experimental values, keeping or discarding suspected inaccurate values.

In this experimental framework, Figs. 1–4 depict the deduced PQVBR/PQCBR ratio of each quality metric for the whole test signal set, along with the corresponding standard deviations. Between the various experimentally derived points of each figure, the best-fit exponential curve of each case has been drawn in order to display the general tendency of the PQVBR/PQCBR ratio. As can be derived by all the cases, the perceptual efficiency of the VBR mode over the CBR is increasing along with the encoding bit rate.

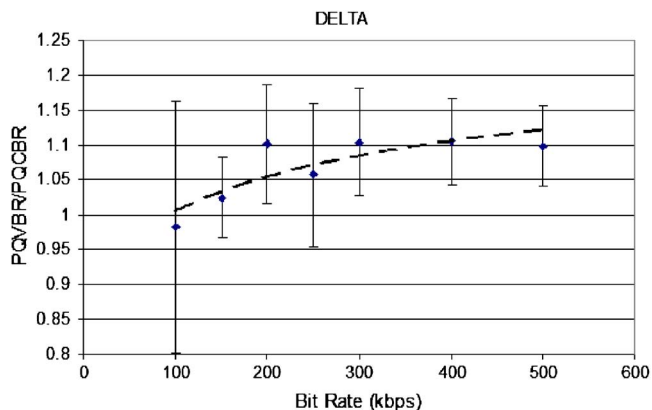


Fig. 3 The PQVBR/PQCBR ratio of the Delta metric for the whole test-signal set.

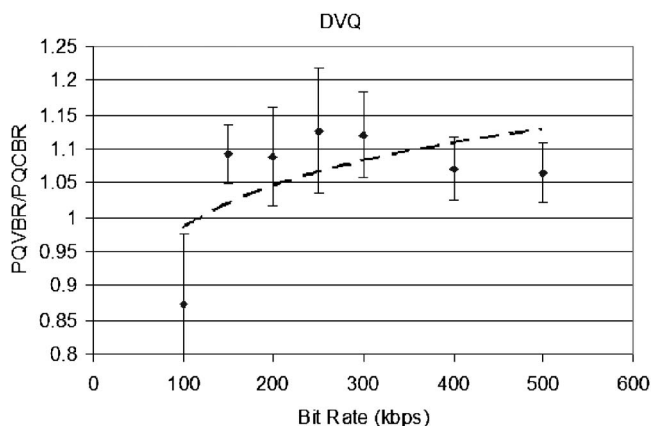


Fig. 4 The PQVBR/PQCBR ratio of the DVQ metric for the whole test-signal set.

More specifically, the VBR generally seems to outperform the CBR, except for very low encoding bit rates (i.e., <125 kbps). Moreover, as can be seen by the experimentally derived points, the PQVBR/PQCBR ratio tends to remain practically constant for high bit rates.

In order to demonstrate the variance in the perceived quality efficiency between the PQVBR and PQCBR, Fig. 5 depicts two representative frames taken from the Suzie sequence encoded at ASP CIF/200 kbps with the CBR [Fig. 5(a)] and the VBR [Fig. 5(b)] mode, respectively (the rest of the encoding configuration is the aforementioned one). Although at first sight no significant difference is noticeable, a closer observation of the two frames, (c) and (d), can reveal a slight perceptual advantage of the VBR over the CBR.

In order to derive a generic quantitative result of this perceptual efficiency of the VBR over the CBR for the CIF

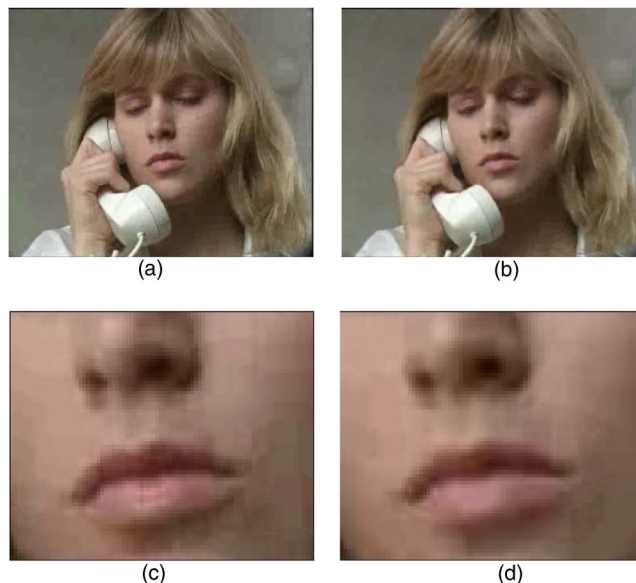


Fig. 5 The PQVBR/PQCBR comparison between two representative frames from the video sequence Suzie.

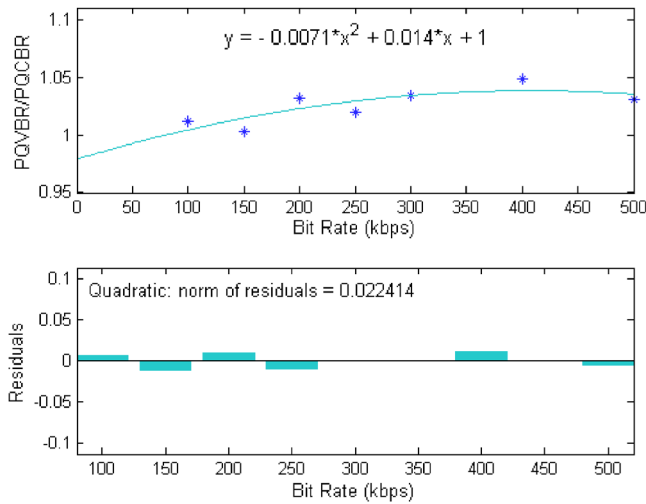


Fig. 6 The PQVBR/PQCBR ratio of MPEG-4 ASP/CIF and the corresponding residuals, between the experimental and theoretical curves.

case, a single graph is extrapolated by Figs. 1–4, which combines into one curve the assessments of each individual quality metric curve.

In order to combine the discrete PQVBR/PQCBR ratios of the various metrics into a common estimation, we use from the error theory the following combining method: considering the x_1, x_2, \dots, x_4 PQVBR/PQCBR ratios of the various video quality metrics at any m th encoding bit rate, with $x_k = \bar{x}_k \pm \delta x_k$, where $k = \{1, 2, 3, 4\}$, we estimate a generic $X_m + dX_m$ PQVBR/PQCBR ratio, based on the following equations:

$$X_m = \frac{\sum_{k=1}^N w_k x_k}{\sum_{k=1}^N w_k}, \quad \text{where } w_k = 1/(\delta x_k)^2$$

and

$$\delta X_m = \sqrt{\frac{1}{N \sum_{k=1}^N w_k}}$$

By applying this method, the experimental points of the PQVBR/PQCBR ratio in Figs. 1–4, which have been derived using the four NR objective quality metrics, provide the generic curve of Fig. 6 and the values of Table 1. The curve of Fig. 6 depicts the PQVBR perceptual efficiency over PQCBR for the case of MPEG-4 ASP/CIF. As can be observed, the PQVBR/PQCBR ratio for the encoding bit-rate area of [100,500] kbps can be successfully approximated by a quadratic-order polynomial of the form

$$y = -0.0071x^2 + 0.014x + 1, \quad 100 \leq x \leq 500, \quad (1)$$

where y is the PQVBR/PQCBR ratio and x is the encoding bit rate.

Table 1 The generic CIF PQVBR/PQCBR ratio.

Bit Rate (kbps)	Final Weighted Average
100	1.01124±0.00891
150	1.00307±0.01146
200	1.03195±0.01538
250	1.01919±0.01158
300	1.03337±0.01159
400	1.04887±0.01747
500	1.03026±0.00997

Thus by using Eq. (1), it is possible to analytically calculate the perceptual efficiency of the VBR over the CBR for the MPEG-4 ASP/CIF case at a pre-encoding stage. The efficiency of the specific theoretical approximation can be observed by the corresponding residuals, shown in Fig. 6, where the norm of the residuals is 0.022414, demonstrating a good match between the experimental and the theoretical results.

Elaborating more on the deduced results of the PQVBR/PQCBR ratio, it must be noted that the PQVBR outperforms the PQCBR almost for the whole encoding bit-rate area (except for the very low ones, i.e., <100 kbps), but the corresponding better perceptual efficiency of the PQVBR is not more than 4–5% in comparison to the PQCBR. More specifically, Fig. 6 shows that the efficiency of the PQVBR over the PQCBR remains practically constant for bit rates >200 kbps, proving by this way its better—but limited—perceptual efficiency.

For consistency of this paper, we repeated the same experimental procedure, using the same reference video clips, for the case of the QCIF VBR/CBR at 32 and 64 kbps. The other encoding parameters remained constant and were similar to the aforementioned CIF case. The used reference and encoded sequences are available online for downloading Ref. 20. Then, the deduced encoded streams were used as inputs to the four video quality metrics (i.e., PSNR, SSIM, delta, and VQM). Afterwards, the PQVBR/PQCBR ratio was calculated for each case, following exactly the same experimental procedure. Table 2 depicts the deduced

Table 2 The PQVBR/PQCBR ratio for the QCIF case.

Video Quality Metric	PQVBR/PQCBR ratio 32 kbps	PQVBR/PQCBR ratio 64 kbps
PSNR	1.0218±0.0069	1.0314±0.0037
SSIM	1.0224±0.0044	1.0153±0.0041
Delta	1.1026±0.0573	1.1224±0.0317
VQM	1.0720±0.0351	1.0832±0.0201
Average	1.0231±0.0037	1.0259±0.0027

results, which show that even for the QCIF case, the perceptual efficiency of the VBR over the CBR is retained at similar and even lower to CIF-case levels (i.e., around 2.5%).

4 Conclusions

This paper has presented an analytical and quantitative approach of the perceptual efficiency of the VBR encoding mode over the CBR for MPEG-4 ASP/CIF-QCIF encoded sequences. It shows that the VBR mode provides better perceptual quality than the CBR, but at a constant-limited percentage of approximately 4–5% in comparison to the CBR case for CIF resolution and approximately 2.5% for the QCIF case. Thus, the generally stated opinion that the VBR provides better encoding quality than the CBR has been verified, although it is true from an engineering point of view, from the perceptual aspect (i.e., user perception and satisfaction), that it is practically limited to only a small perceptual enhancement of the VBR over the CBR.

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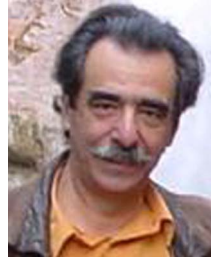
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