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Title: A Regularized Post Filter to Reduce Additive Quantization Noise

Purpose: Proposal

In this proposal, a pixel based regularization algorithm reducing additive quantization noise is proposed, and the results applying the algorithm to the problem for simultaneous reducing the blocking and ringing effects, which are the visually annoying phenomenon of the compressed image using quantization mechanism, is presented. A new functional to utilize the correlation to four spatial direction is defined, and optimal solution is obtained by taking the differential operator to the proposed functional. Furthermore, the choice of the regularization parameter, which is critical in regularization restoration problem, is estimated from the available overhead information in decoder, resulting in reducing the computational cost. The experimental results show the capability and efficiency of the proposed algorithm.

1. Introduction

Quantization is the key step in every image and video compression algorithm. However, as the bit rate is lowered, most of the existing techniques, as well as, the current standards, produces highly visible degradation in the reconstructed images due primarily to the information loss caused by the quantization process [1].

Quantization is applied directly on the image and video pixel intensities or any transformation or series of transformations of these intensities which result, for example, in the transformed and motion compensated frame difference or in a multiresolution wavelet representation. The transformation may be applied to the whole image or to overlapping or non-overlapping segments (blocks) of the image or video frame. It is the nonlinear quantization operation, which reduces the information representing the source image. The coarser the quantization the higher the compression; however, the larger the amount of information loss, and therefore, the more visible and objectionable the compression artifacts.

Two main types of artifacts are encountered in hybrid video coders such as the ones that are included in all the video compression standards. These artifacts are blocking and ringing artifacts. Blocking artifact result from the independent processing of each block of an image, and the information loss of low frequency components. On the other hand, ringing artifacts typically appear as sharp oscillations along the edge of an object moving on a relatively flat background, due to the information loss of high frequency components.

The reduction of the artifacts or recovery of the quantization information has been appeared in the literature [2,3,4,5]. The approaches can be classified into two categories. Those are linear or nonlinear filtering, and regularization restoration approach. The former has advantage on the computational cost. However, due to the lack of the adaptivity, the performance is not satisfactory. On the other hands, the later has disadvantage on the complexity. Therefore, it is required to consider the trade-off of the above two issues.

The recovery of the quantization information loss is ill conditioned, and in order to obtain a desirable solution, prior information about the original image and the noise should be utilized. However, this prior information may be limited. Therefore, in order to achieve the best possible results, this prior information must be extracted from the available data. The regularization theory has been used to replace the ill-posed problem with well-posed problem by incorporating the smoothing constraint into the solution [6,7,8]. As pointed out, the typical regularization approach has trouble in the complexity, which mainly comes from the use of iterative technique and the choice of the regularization parameters [9].

In previous meeting, a pixel based regularization algorithm to simultaneously reduce the blocking and ringing artifacts was proposed [10]. It was shown that the algorithm is efficient and the results are satisfactory. However, since the solution is always affected by the smoothing functional, the results may be over-smoothed. The new proposed functional therefore is defined is such in a way that the smoothing functional and the fidelity functional is simultaneously controlled by the regularization parameter, resulting in avoiding the over-smoothness depending on a priori information. Also, in order to reduce the computational cost, the pixels belonging to *not coded* macro block are not processed, but represented by pixels of the previous recovered image.

This proposal is organized as follows. In section 2, the new regularization functional to be minimized is defined and its properties are discussed. Also, the choice of the regularization parameters is described in Section 3. Finally, experimental results of the proposed method and conclusions are presented in section 4.

2. A Pixel Based Regularized Smoothing Functional

The quantization process makes an image degraded, and the degradation model can be written as

$$g(i,j) = f(i,j) + n(i,j), \qquad (1)$$

where g,f, and n represent the compressed image, the original image, and quantization error, respectively. Also, (i,j) denotes two-dimensional imaging coordinate. As mentioned before, since the regularization smoothing functional proposed in [10] results in over-smoothness in edge area and less-smoothness in blocky and ringing area due to consistent use of the smoothing functional. Therefore, the new regularization functional that we propose is defined as

$$M(f(i,j)) = M_L(f(i,j)) + M_R(f(i,j)) + M_U(f(i,j)) + M_D(f(i,j)), \qquad (2)$$

where

$$\begin{aligned}
M_L(f(i,j)) &= (1-\alpha_L(f(i,j))[f(i,j)-g(i,j)]^2 + \alpha_L(f(i,j))[f(i,j)-f(i,j-1)]^2,\\
M_R(f(i,j)) &= (1-\alpha_R(f(i,j))[f(i,j)-g(i,j)]^2 + \alpha_R(f(i,j))[f(i,j)-f(i,j+1)]^2,\\
M_U(f(i,j)) &= (1-\alpha_U(f(i,j))[f(i,j)-g(i,j)]^2 + \alpha_U(f(i,j))[f(i,j)-f(i-1,j)]^2,\\
M_D(f(i,j)) &= (1-\alpha_D(f(i,j))[f(i,j)-g(i,j)]^2 + \alpha_D(f(i,j))[f(i,j)-f(i+1,j)]^2. \qquad (3)
\end{aligned}$$

In Eq. (3), $M_L(f(i,j)), M_R(f(i,j)), M_U(f(i,j)), M_D(f(i,j))$ are regularization functionals to incorporate smoothness to left, right, up, and down directions into the solution, and the first term of each functional denotes the fidelity to the data and the second term represents the smoothness to the each direction. Also, $\alpha_L(f(i,j)), \alpha_R(f(i,j)), \alpha_U(f(i,j)), \alpha_U(f(i,j))$ are the regularization parameters to control the trade-off between the two conflict functionals. In Eq. (3), depending on the regularization parameter, the recovered image can be as close as possible to the compressed image or it can be represented by the four neighboring pixels. The regularization parameters have been determined by a prior information, and those are estimated by quantization parameter in this application. In order to obtain an estimated image, the differentiation of Eq. (2) with respect to $f(i,j)$ results in

$$f(i,j) = \frac{(4-\alpha_{TOT}(f(i,j))g(i,j) + \alpha_L(f(i,j))f(i,j-1) + \alpha_R(f(i,j)f(i,j+1) + \alpha_U(f(i,j))f(i-1,j) + \alpha_D(f(i,j))f(i+1,j)}{4}, \qquad (4)$$

where $\alpha_{TOT}(f(i,j)) = \alpha_L(f(i,j)) + \alpha_R(f(i,j)) + \alpha_U(f(i,j)) + \alpha_D(f(i,j))$. Since $f(i,j-1)$, $f(i,j+1)$, $f(i-1,j)$,$f(i+1,j)$ are not available, the observed pixels, $g(i,j-1)$,$g(i,j+1)$,$g(i-1,j)$,$g(i+1,j)$ are instead used in this proposal for efficiency. Then, the estimation of the proposed algorithm become

$$f(i,j)=\frac{(4-\alpha_{TOT}(f(i,j))g(i,j)+\alpha_L(f(i,j))g(i,j-1)+\alpha_R(f(i,j)g(i,j+1)+\alpha_U(f(i,j))g(i-1,j)+\alpha_D(f(i,j))g(i+1,j)}{4}. \quad (5)$$

In general, each macro block can be classified into two coding mode; *coded* mode (intra and inter) and *not coded* mode. Since *not coded* macro block means that the pixels belonging to the macro block are highly correlated to the pixels locating at the same position of the previous frame. Also, *not coded* macro blocks are crowded in stationary region, such as, background or non-moving object. The region of the previous recovered image, therefore, can be utilized for the pixels of the not coded macro block, so that the complexity is reduced. Then, the proposed algorithm is implemented as

$$f(i,j)=\left[\begin{array}{ll} f_p(i,j), & \text{if f(i,j) is element of not coded macro block} \\ & \text{Eq. (5),otherwise} \end{array}\right., \quad (6)$$

where f_p denotes the previous recovered image.

In order to obtain the estimation in Eq. (5), the four directional regularization parameters are required. In next section, the choice of the parameters will be discussed.

3. Choice of Regularization Parameters

The regularization parameters to control the relative contribution between the fidelity functional and the smoothing functional in each direction can be determined by available information in decoder. Since the information loss of an original image is due to the quantization parameter, *n(i,j)* in Eq. (1) should be proportional to the quantization parameter. Let QP_l be quantization parameter of l-th macro block which includes *f(i,j)*. According to typical property of the regularization theory, the regularization parameter in each direction can be written as

$$\begin{aligned}
\frac{1-\alpha_L(f(i,j))}{\alpha_L(f(i,j))} &= \frac{[f(i,j)-g(i,j-1)]^2}{[f(i,j)-g(i,j)]^2} = \frac{[f(i,j)-g(i,j-1)]^2}{\phi(QP_l)}, \\
\frac{1-\alpha_R(f(i,j))}{\alpha_R(f(i,j))} &= \frac{[f(i,j)-g(i,j+1)]^2}{[f(i,j)-g(i,j)]^2} = \frac{[f(i,j)-g(i,j+1)]^2}{\phi(QP_l)}, \\
\frac{1-\alpha_U(f(i,j))}{\alpha_U(f(i,j))} &= \frac{[f(i,j)-g(i-1,j)]^2}{[f(i,j)-g(i,j)]^2} = \frac{[f(i,j)-g(i-1,j)]^2}{\phi(QP_l)}, \\
\frac{1-\alpha_D(f(i,j))}{\alpha_D(f(i,j))} &= \frac{[f(i,j)-g(i+1,j)]^2}{[f(i,j)-g(i,j)]^2} = \frac{[f(i,j)-g(i+1,j)]^2}{\phi(QP_l)},
\end{aligned} \quad (7)$$

where $\phi(QP_l)$ represents a function of QP_l. If the additive noise is symmetrically distributed in spatial domain, each denominator of Eq. (6) should be same value. However, the problem at hand is different in that different degree of smoothness depending on the pixel position is required. In other words, larger smoothness is necessary between block to reduce blocking artifacts, and relatively smaller smoothness is required within block to reduce ringing artifacts. Therefore, according to the pixel position, different degree of the smoothness is used such as

$$\begin{aligned}
\alpha_L &= \frac{K_L QP_l^2}{[g(i,j)-g(i,j-1)]^2+K_L QP_l^2}, \\
\alpha_R &= \frac{K_R QP_l^2}{[g(i,j)-g(i,j+1)]^2+K_R QP_l^2}, \\
\alpha_U &= \frac{K_U QP_l^2}{[g(i,j)-g(i-1,j)]^2+K_U QP_l^2}, \\
\alpha_D &= \frac{K_D QP_l^2}{[g(i,j)-g(i+1,j)]^2+K_D QP_l^2},
\end{aligned} \quad (8)$$

where K_L, K_R, K_U, K_D denote constants which are differently chosen by position of *g(i,j)* . Those are

$$K_L = \begin{cases} 9, & \text{if } j \bmod 8 = 0 \\ 1, & \text{otherwise} \end{cases},$$

$$K_R = \begin{cases} 9, & \text{if } j \bmod 8 = 1 \\ 1, & \text{otherwise} \end{cases},$$

$$K_U = \begin{cases} 9, & \text{if } i \bmod 8 = 0 \\ 1, & \text{otherwise} \end{cases},$$

$$K_D = \begin{cases} 9, & \text{if } i \bmod 8 = 1 \\ 1, & \text{otherwise} \end{cases}.$$

In summary, Eqs. (5), (6), and (8) are necessary for the proposed algorithm to be implemented.

4. Experimental Results and Conclusions

The proposed post filter is applied to TMN8, and compared with several options such as Annex J, Modified annex J, Modified annex J+deringing filter, and deringing filter that is appeared in Q15-D-65. The proposed algorithm is compared with the other options in terms of PSNR, complexity (instruction number and memory bandwidth), and bit rates. From the experimental results, it is clear that the proposed algorithm outperforms the other options, and its complexity is decreased due to the not coded block as QP value is larger. Therefore, the proposed algorithm is very efficient, as the target bit rates is lower. Also, subject quality with the proposed algorithm is very satisfactory and always better than the other options.

In this proposal, a regularized post-filtering algorithm to simultaneously reduce blocking and ringing artifacts is proposed, and the performance is compared with the several options. The experimental results show the capability of the proposed algorithm in terms of subject and object qualities and complexity. Even though this algorithm is applied to the compressed images using hybrid MC/DCT mechanism, it can be utilized for reducing quantization noise by changing the constants in Eq. (8) of any new codec using quantization mechanism.

References

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Approach A: TMN8
Approach B: TMN8 + Annex J
Approach C: TMN8 + Modified Annex J
Approach D: TMN8 + Modified Annex J + Post Filter (D65).
Approach E: TMN8 + Post Filter (D65)
Approach F: TMN8 + **LGE Post Filter**

<u>Container Sequence (QCIF), 300 frames, 10 frame rate/sec</u>

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	36.73	41.43	41.01	36.56	41.38	41.08	36.53	41.47	41.14	36.61	41.52	41.16	36.79	41.51	41.07	**36.98**	**41.71**	**41.44**
10	32.34	38.45	37.77	32.21	38.51	38.11	32.23	38.74	38.08	32.32	38.51	38.11	32.45	38.51	37.91	**32.52**	**38.78**	**38.14**
15	30.02	36.90	36.21	29.91	37.33	36.65	29.90	37.41	36.62	30.01	37.02	36.60	30.15	36.89	36.36	**30.20**	**37.23**	**36.57**
25	27.36	35.16	34.18	27.26	35.91	34.82	27.26	35.86	34.75	27.32	35.52	34.51	27.45	35.32	34.28	**27.43**	**35.53**	**34.54**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	9.65	5.43	9.93	5.45	36.60	20.66	26.67	15.20	**9.38**	**5.09**
10	N/A	N/A	5.79	3.26	5.95	3.26	31.62	18.46	26.67	15.20	**5.25**	**2.85**
15	N/A	N/A	5.08	2.86	5.20	2.85	31.87	18.06	26.67	15.20	**4.47**	**2.43**
25	N/A	N/A	4.07	2.30	4.26	2.33	30.93	17.54	26.67	15.20	**3.39**	**1.85**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	62.16	61.70	61.82	61.82	62.16	**62.16**
10	22.92	22.98	23.11	23.11	22.98	**22.98**
15	13.93	14.23	14.30	14.30	13.93	**13.93**
25	7.35	7.74	7.74	7.74	7.35	**7.35**

Hall monitor (QCIF), 300 frames, 10 frame rate/sec

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	37.82	39.90	41.73	37.57	40.24	42.16	37.54	40.33	42.13	37.65	40.43	42.23	37.93	40.04	41.92	**38.28**	**40.35**	**42.10**
10	33.14	37.46	39.85	33.20	37.96	39.93	33.14	37.92	39.92	33.24	37.84	39.92	33.28	37.64	40.01	**33.50**	**37.78**	**39.93**
15	30.79	36.41	39.60	30.95	36.84	39.60	30.90	36.79	39.50	30.96	36.80	39.60	30.91	36.78	39.77	**31.09**	**36.76**	**39.65**
25	27.89	35.20	39.10	28.09	35.44	39.33	28.05	35.42	39.26	28.09	35.47	39.35	27.96	35.38	39.24	**28.12**	**35.38**	**39.19**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	8.80	4.96	9.09	4.98	35.76	20.19	26.67	15.21	**8.18**	**4.44**
10	N/A	N/A	3.62	2.03	3.84	2.10	30.51	17.31	26.67	15.21	**2.99**	**1.63**
15	N/A	N/A	2.96	1.67	3.05	1.68	29.72	16.89	26.67	15.21	**2.35**	**1.28**
25	N/A	N/A	2.45	1.38	2.51	1.38	29.18	16.59	26.67	15.21	**2.07**	**1.14**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	56.90	54.75	54.72	54.72	56.90	**56.90**
10	22.74	21.81	21.92	21.92	22.74	**22.74**
15	14.27	13.86	13.96	13.96	13.96	**13.96**
25	8.02	8.09	8.06	8.06	8.02	**8.02**

Foreman Sequence (QCIF), 300 frames, 10 frame rate/sec

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	36.40	40.64	41.17	36.49	40.89	41.56	36.49	40.93	41.52	36.51	40.84	41.50	36.43	40.65	41.24	**36.67**	**40.86**	**41.50**
10	32.05	37.73	37.97	32.17	38.08	38.36	32.16	38.15	38.38	32.13	38.10	38.31	32.09	38.83	38.07	**32.27**	**38.02**	**38.29**
15	30.01	36.46	36.51	30.13	36.94	36.89	30.17	36.89	36.93	30.06	36.89	36.82	30.01	36.60	36.62	**30.20**	**36.77**	**36.82**
25	27.71	35.11	34.54	27.69	35.29	34.88	27.82	35.44	34.93	27.68	35.50	34.95	27.68	35.22	34.67	**27.85**	**35.36**	**34.84**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	12.41	6.99	12.75	6.99	39.42	22.19	26.67	15.20	**13.71**	**7.43**
10	N/A	N/A	11.92	6.72	12.25	6.71	38.92	21.91	26.67	15.20	**12.88**	**6.98**
15	N/A	N/A	11.61	6.54	11.95	6.54	38.62	21.75	26.67	15.20	**12.36**	**6.69**
25	N/A	N/A	11.08	6.24	11.36	6.22	38.03	21.45	26.67	15.20	**11.69**	**6.33**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	160.66	148.88	148.59	148.59	160.66	**160.66**
10	67.14	63.68	68.66	68.66	67.14	**67.14**
15	42.06	41.08	41.04	41.04	42.06	**42.06**
25	25.10	25.57	25.18	25.10	25.10	**25.10**

News Sequence (QCIF), 300 frames, 10 frame rate/sec

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	37.05	40.21	40.77	37.05	40.35	41.00	37.00	40.32	41.03	37.07	40.32	40.94	37.11	40.23	40.80	**37.41**	**40.67**	**41.09**
10	32.37	36.51	37.46	32.36	36.82	37.80	32.34	36.82	37.85	32.41	36.73	37.63	32.46	36.55	37.44	**32.64**	**36.98**	**37.70**
15	30.06	34.59	35.95	30.13	35.22	36.43	30.10	35.25	36.41	30.15	35.11	36.14	30.16	34.71	36.06	**30.30**	**34.97**	**36.26**
25	27.30	32.45	34.05	27.32	33.16	34.63	27.35	33.11	34.62	27.24	32.98	34.38	27.36	32.60	34.36	**27.45**	**32.89**	**34.38**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	7.80	4.40	8.08	4.43	34.75	19.64	26.67	15.21	**9.38**	**5.09**
10	N/A	N/A	6.43	3.62	6.66	3.65	33.33	18.86	26.67	15.21	**5.77**	**3.13**
15	N/A	N/A	5.62	3.17	5.82	3.19	32.49	18.40	26.67	15.21	**4.94**	**2.68**
25	N/A	N/A	4.67	2.63	4.74	2.60	31.41	17.81	26.67	15.21	**3.98**	**2.17**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	87.55	84.18	84.35	84.35	87.55	**87.55**
10	37.46	36.39	36.61	36.61	37.46	**37.46**
15	22.73	22.43	22.62	22.62	22.73	**22.73**
25	12.14	12.83	12.72	12.72	12.14	**12.14**

Silent voice Sequence (QCIF), 300 frames, 15 frame rate/sec

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	36.56	39.36	40.39	36.48	39.73	40.73	36.52	39.78	40.82	36.51	39.58	40.72	36.58	39.29	40.40	**36.85**	**39.59**	**40.72**
15	30.02	34.57	36.28	30.21	34.88	36.52	30.23	34.91	36.56	30.12	34.76	36.55	30.04	34.74	36.58	**30.29**	**34.87**	**36.60**
25	27.70	33.13	35.09	27.86	33.43	35.50	27.88	33.36	35.55	27.68	33.06	35.46	27.72	33.24	35.35	**27.90**	**33.32**	**35.36**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	12.30	6.93	12.48	6.84	52.48	29.65	40.00	22.81	**11.00**	**5.97**
15	N/A	N/A	8.39	4.72	8.45	4.63	48.45	27.44	40.00	22.81	**7.74**	**4.20**
25	N/A	N/A	7.08	3.99	7.17	3.92	47.17	26.73	40.00	22.81	**6.56**	**3.56**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	98.73	96.27	96.16	96.16	98.73	**98.73**
15	24.57	24.82	24.76	24.76	24.57	**24.57**
25	14.26	15.07	15.11	15.11	14.26	**14.26**

Glasgow Sequence (QCIF), 750 frames, 10 frame rate/sec

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	35.68	40.22	41.80	35.73	40.58	42.18	35.71	40.57	42.14	35.72	40.56	42.17	35.70	40.31	41.97	**36.00**	**40.54**	**42.16**
15	28.77	35.66	37.83	28.94	36.12	38.24	28.94	36.05	38.20	28.91	36.00	38.30	28.83	36.00	38.32	**29.03**	**36.07**	**38.25**
25	26.38	33.87	36.28	26.59	34.19	36.58	26.60	34.17	36.55	26.55	34.25	36.67	26.43	34.28	36.72	**26.59**	**34.25**	**36.63**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	12.30	6.93	12.29	6.74	38.96	21.95	26.67	15.21	**13.04**	**7.07**
15	N/A	N/A	8.39	4.72	10.76	5.90	37.43	21.11	26.67	15.21	**11.07**	**6.00**
25	N/A	N/A	7.08	3.99	10.11	5.54	36.78	20.75	26.67	15.21	**10.44**	**5.66**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	254.10	243.91	244.11	244.11	254.10	**254.10**
15	66.02	64.07	64.03	64.03	66.02	**66.02**
25	35.72	35.70	35.76	35.76	35.72	**35.72**

Irene Sequence (CIF), 500 frames, 30 frame rate/sec

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	38.91	41.41	41.17	38.99	41.51	41.40	38.97	41.40	41.37	39.02	41.35	41.33	38.98	41.44	41.21	**39.21**	**41.75**	**41.53**
15	33.20	36.54	36.10	33.39	36.95	36.54	33.42	36.90	36.54	33.30	36.78	36.19	33.24	36.61	36.13	**33.41**	**36.93**	**36.47**
25	31.05	34.59	33.99	31.24	35.16	34.55	31.30	35.15	34.56	31.20	35.04	34.07	31.06	34.69	34.03	**31.22**	**34.91**	**34.31**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	72.00	40.56	74.43	40.79	394.45	223.26	320.02	182.47	**69.24**	**37.60**
15	N/A	N/A	52.05	29.32	53.21	29.16	373.23	65.29	320.02	182.47	**48.47**	**26.37**
25	N/A	N/A	44.12	24.38	46.84	25.66	366.86	208.13	320.02	182.47	**41.95**	**22.85**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	638.98	626.75	626.27	626.27	636.98	**636.98**
15	141.24	143.20	142.32	142.32	141.24	**141.24**
25	82.18	86.17	85.82	86.17	82.18	**82.18**

<u>Paris Sequence (CIF), 900 frames, 15 frame rate/sec</u>

PSNR Comparison

QP	A			B			C			D			E			**F**		
	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr	Y	Cb	Cr
5	36.28	39.50	39.65	36.05	39.57	39.76	36.08	39.61	39.86	36.13	39.62	39.87	36.34	39.55	39.71	**36.60**	**39.87**	**40.07**
15	28.82	33.55	34.12	28.71	33.96	34.48	28.68	34.01	34.55	28.73	33.80	34.33	28.89	33.69	34.23	**29.00**	**33.94**	**34.55**
25	25.99	31.36	32.14	25.88	31.81	32.57	25.89	31.82	32.60	25.91	31.70	32.44	26.03	31.49	32.26	**26.05**	**31.71**	**32.52**

Complexity comparison

QP	A		B		C		D		E		**F**	
	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)	Instruction Number (MIPS)	Memory Bandwidth (Mbytes/s)
5	N/A	N/A	51.68	29.12	52.71	28.88	212.72	120.14	160.02	91.26	**43.07**	**23.37**
15	N/A	N/A	30.32	17.08	31.28	17.14	191.30	108.40	160.02	91.26	**25.55**	**13.90**
25	N/A	N/A	25.15	14.17	25.80	14.14	185.82	105.40	160.02	91.26	**20.88**	**11.37**

Bit rates (kbits/sec)

QP	A	B	C	D	E	**F**
5	510.38	499.32	498.11	498.11	510.38	**510.38**
15	124.70	123.29	123.44	123.44	124.70	**124.70**
25	60.03	62.97	62.93	62.93	60.03	**60.03**