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Coding of Still Pictures

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TITLE: Fixed Length Coding by Nonuniform Scalar Quantization in JPEG2000

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1 Introduction: VCLC vs. FLC

In mobile and wireless transmission, entropy coding (Variable Length Coding – VLC) is prone to transmission errors due to loss in synchronization. To make the codec more robust two solutions have been discussed so far.

The first method alleviates the degradation due to loss of resynchronization by smart data partitioning and by inserting resynchronization markers into the bit stream [1]. This achieves an improvement in PSNR of about 10 dB when the image is transmitted over BSC and burst channels, respectively, while in the error free case coding efficiency can be approximately maintained[1]. This codec is denoted as *baseline codec* in the following.

The second method replaces the TCQ / VLC by a PVQ / FLC [2], described in [3] and [4]. Using this codec, an improvement of PSNR up to 15 dB can be achieved for channel transmission, while in the error free case the codec performs about 0.8 dB poorer than the one with resynchronization. This codec is called the *NTNU codec*. Although it offers superior performance in the presence of channel errors, it has been viewed by some members of the JPEG community as a too radical departure from the algorithm presently used in the VM0. However, we will still show results also from this codec in this report, in order to get a reliable comparison with the VM0 codec.

An alternative to these two codecs is the use of *fixed-length scalar quantization (SCQ)*. SCQ will typically result in a somewhat reduced coding efficiency in the error-free case, since we no longer exploit dimensionality or statistical inter-coefficient dependencies. However, it will be very robust towards channel errors, since each bit error only affects the value of *one* wavelet coefficient. SCQ also has the virtue of *low complexity* compared to the TCQ, and it represents less of a departure from the present VM0, which in fact already has a scalar quantization switch. It is therefore our opinion that SCQ should be considered as an option for the applications where the error-free case is of no practical interest, such as wireless and mobile transmission of images.

2 Replacing the VLC with nonuniform scalar quantization

The current "default" VM0 consists of a TCQ combined with a succeeding binary adaptive arithmetic (BP) encoder, providing variable-length code words. After each resynchronization marker the context probability models are re-initialized to a uniform probability distribution, since there are no (or neglegible) dependencies among the sequences containing the DWT coefficients.

In the VM0, bit allocation is performed with respect to a constraint on the target bit rate and assuming VLC for the coding gain. The R-D performance for each sequence is predicted using analytic expressions derived empirically from generalized Gaussian probability functions, providing a minimum predicted MSE. Therefore, it is not possible to take out only the VLC and insert FLC instead, since the performance of the TCQ is absolutely dependent on VLC.

We therefore consider the replacement of both TCQ / FLC, by *scalar* quantization (SCQ) of the wavelet coefficients. We then have the options of using either uniform quantizers[2] followed by entropy coding, or *pdf*[3]*-optimized* quantizers, socalled *Lloyd-Max-quantizers* [5, 6]. Only the second option is relevant for our needs, as the first just results in another variable-length coder.

A pdf-optimized quantizer minimizes the mean squared quantization error for a given code word length. It has *non-uniform* spacing of the quantization levels, i.e. decision intervals of varying size, if

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[1] There will be some amount of overhead which will influence the rate-distortion curve slightly.

[2] I.e. quantizers with uniformly spaced quantization levels.

[3] Pdf is an abbreviation of "Probability density function".

the probability density function (pdf) for which it is optimized is not uniform. Typically the quantization levels will be close to each other in regions with a high probability density, and far apart in regions with a low probability density. This will make the resulting (fixed-length) codewords *approximately equiprobable*, which eliminates the need for entropy (and thus variable length) coding.

Since the pdfs of the wavelet coefficients within a subband are known to be well-approximated by *Laplacian* densities (save for the LP-LP-band, which is more closely approximated by a *uniform* density), we may in our case employ well-known closed form solutions for the Lloyd-Max quantization and decision levels (which in general must be found in an iterative manner).

As an alternative to TCQ and pVQ we thus propose an encoder which consists of

- a Mallat (7,9) wavelet transform,
- a *bit allocation* procedure,
- scalar Lloyd-Max quantization optimized for Laplacian densities for the LP-HP and HP-HP wavelet coefficients,
- scalar uniform quantization for the LP-LP band.

The task of the bit allocation procedure is to distribute the bits available for coding of the wavelet coefficients (the *bit pool*) in as useful a way as possible among the wavelet coefficients. The chosen procedure works on 4×4 subblocks of the wavelet transformed image. Since the LP-LP-band is of such special perceptual importance, it is treated separately, and is uniformly quantized with 7 bits per coefficient. The other bands are split into 4×4 subblocks, and the variance within each subblock is computed. The subblocks are sorted in order of decreasing variance. We allocate 1 bit per coefficient to the subblock with the highest variance. Then we divide the variance for this block by 2, to account for the fact that the quantization residual after an optimized 1-bit quantization will have a variance which is one half of the variance of the signal being quantized. The subblocks are subsequently sorted in order of decreasing variance once again, 16 bits are subtracted from the bit pool, and the above steps are repeated in a loop until the bit pool is empty. When all bits in the pool have been used, an integer number of B_n bits per coefficient, where B_n typically lies in the range 0 – 6, have been allocated to subblock n. We then employ a B_n-bit Lloyd-Max quantizer for block n. When performing the actual quantization, each subblock is normalized to unit variance, and quantizers optimized for correspondingly normalized Laplacian sources are used. This is done to ensure that the quantizers will properly cover the dynamic range of all blocks. However, it means that the subblock variances (or standard deviations) – plus, of course, the number of bits used for each subblock – must then be transmitted as side information, which is assumed to be entropy coded, put in the code header, and protected separately. The resulting codec is denoted by CE.

3 Testing

The following tests have been performed:

1. VM0 (TCQ/FLC) vs. NTNU (PVQ/FLC)
2. CE (SCQ/FLC) vs. baseline (TCQ/VLC)
3. CE (SCQ/FLC) vs. VM0 (using the imbedded scalar quantizer of the VM0)

The results have been obtained following the requirements given in the document *Common testing conditions for error resilience core experiments* as agreed by the *Ad-Hoc Group on Error Resilience*.

Parameters are: *-a -e 0.002 0 -s 2048 2560 -u8 -mallat -w7x9 -bp_r* for the baseline, *-a -e 0.002 0 -s 2048 2560 -u8 -mallat -w7x9* for the VM0, and *-p -n 2048 -m 2560* for the NTNU codec, respective.

The PSNRs are from the average of 100 runs of simulation unless otherwise noted.

The channels are simulated using the software simulation package distributed to the JPEG community by *NTT-DoCoMo* [7, 8]. The header bits have not been affected by the channel errors. In real systems the header might be protected separately with higher levels of protection.

4 Results

4.1 VM0 (TCQ/FLC) vs. NTNU (PVQ/FLC)

This simulation (Tab. 1 to 3) compares the newly (May 15th) released VM0 with the current version of the NTNU codec to show the superiority of the NTNU codec if the image is transmitted over a BSC or burst channel, respectively.

The average gain of the NTNU codec over the VM0 is 4.78 dB in the presence of channel errors, while in the error free case there is an average degradation of 0.80 dB compared with the VM0.

Please note that running the VM0 under channel simulations has produced several core dumps (*tilt* - *t*otal *i*mage *l*oss *t*ermination) which are denoted by the number in parenthesis after each PSNR value.

bike				0.125 bpp			0.5 bpp		
	ber	length		NTNU	VM0	gain	NTNU	VM0	gain
burst	0.001	1	max	24.80	19.80	5.00	30.70	17.41	13.29
	0.001	1	**mean**	**24.03** *(0)*	**16.40** *(0)*	**7.63**	**28.62** *(0)*	**15.47** *(0)*	**13.15**
	0.001	1	min	19.49	12.24	7.25	23.60	10.97	12.63
	0.001	1	stddev	0.98	1.15	-0.17	2.04	1.30	0.74
	0.001	10	max	24.87	25.07	-0.2	31.26	24.79	6.47
	0.001	10	**mean**	**24.41** *(0)*	**21.69** *(0)*	**2.72**	**30.53** *(0)*	**20.54** *(0)*	**9.99**
	0.001	10	min	17.44	13.52	3.92	18.75	12.92	5.83
	0.001	10	stddev	1.25	2.13	-0.88	1.42	1.94	-0.52
	0.01	1	max	22.77	14.97	7.90	24.53	14.41	10.12
	0.01	1	**mean**	**20.05** *(0)*	**12.51** *(0)*	**7.54**	**20.96** *(0)*	**12.19** *(0)*	**8.77**
	0.01	1	min	17.91	10.97	6.94	17.73	10.97	6.76
	0.01	1	stddev	1.13	1.25	-0.12	1.23	1.17	0.06
	0.01	10	max	24.39	18.43	5.96	28.93	17.41	11.52
	0.01	10	**mean**	**22.28** *(0)*	**15.73** *(0)*	**6.55**	**25.21** *(0)*	**15.05** *(1)*	**10.16**
	0.01	10	min	17.09	10.97	6.12	16.34	10.97	5.37
	0.01	10	stddev	1.93	1.78	0.15	2.96	1.51	1.45
BSC	0.001		max	22.84	14.07	8.77	24.72	13.96	10.76
	0.001		**mean**	**20.33** *(0)*	**12.44** *(2)*	**7.89**	**20.64** *(0)*	**12.27** *(0)*	**8.37**
	0.001		min	17.24	10.97	6.27	17.90	10.97	6.93
	0.001		stddev	1.10	1.08	0.02	1.39	1.07	0.32
	0.01		max	13.99	10.97	3.02	13.20	10.97	2.23
	0.01		**mean**	**12.85** *(0)*	**10.97** *(0)*	**1.88**	**12.25** *(0)*	**10.97** *(0)*	**1.28**
	0.01		min	11.83	10.97	0.86	11.55	10.97	0.58
	0.01		stddev	0.42	0.00	0.42	0.33	0.00	0.33
	0.1		max	9.31	10.97	-1.66	9.20	10.97	-1.77
	0.1		**mean**	**9.08** *(0)*	**10.97** *(0)*	**-1.89**	**8.95** *(0)*	**10.97** *(0)*	**-2.02**
	0.1		min	8.77	10.97	-2.20	8.62	10.97	-2.35
	0.1		stddev	0.11	0.00	0.11	0.09	0.00	0.09
error free				**24.87**	**25.65**	**-0.78**	**31.27**	**32.81**	**-1.54**

Table 1: PSNR [dB] results for *bike*

cafe				0.125 bpp			0.5 bpp		
	ber	length		NTNU	VM0	gain	NTNU	VM0	gain
burst	0.001	1	max	20.30	16.27	4.03	25.87	15.80	10.07
	0.001	1	**mean**	**20.11** *(0)*	**14.34** *(1)*	**5.77**	**24.79** *(0)*	**14.05** *(0)*	**10.74**
	0.001	1	min	19.33	10.89	8.44	21.70	11.77	9.93
	0.001	1	stddev	0.21	1.16	-0.95	0.95	0.84	0.11
	0.001	10	max	20.34	20.50	-0.16	26.08	20.73	5.35
	0.001	10	**mean**	**20.24** *(0)*	**18.26** *(0)*	**1.98**	**25.55** *(0)*	**18.03** *(0)*	**7.52**
	0.001	10	min	19.43	11.96	7.47	19.81	12.22	7.59
	0.001	10	stddev	0.17	1.54	-1.37	1.13	1.21	-0.08
	0.01	1	max	19.13	13.45	5.68	22.32	13.09	9.23
	0.01	1	**mean**	**18.24** *(0)*	**11.64** *(2)*	**6.60**	**19.97** *(0)*	**11.64** *(0)*	**8.33**
	0.01	1	min	16.77	9.16	7.61	17.60	10.89	6.71
	0.01	1	stddev	0.50	0.73	-0.23	0.95	0.60	0.35
	0.01	10	max	20.07	16.18	3.89	24.70	15.58	9.12
	0.01	10	**mean**	**19.25** *(0)*	**13.83** *(1)*	**5.42**	**22.56** *(0)*	**13.68** *(0)*	**8.88**
	0.01	10	min	15.67	10.89	4.78	18.07	10.89	7.18
	0.01	10	stddev	0.83	1.35	-0.52	1.51	1.08	0.43
BSC	0.001		max	19.37	12.76	6.61	22.53	12.30	10.23
	0.001		**mean**	**18.21** *(0)*	**11.75** *(2)*	**6.46**	**20.12** *(0)*	**11.57** *(1)*	**8.55**
	0.001		min	17.00	10.89	6.11	17.55	10.89	6.66
	0.001		stddev	0.54	0.57	-0.03	1.02	0.51	0.51
	0.01		max	13.58	11.02	2.56	13.27	10.89	2.38
	0.01		**mean**	**12.81** *(0)*	**10.89** *(0)*	**1.92**	**12.39** *(0)*	**10.89** *(1)*	**1.50**
	0.01		min	11.90	10.89	1.01	11.73	10.89	0.84
	0.01		stddev	0.33	0.01	0.32	0.30	0.00	0.30
	0.1		max	9.07	10.89	-1.82	8.88	10.89	-2.01
	0.1		**mean**	**8.91** *(0)*	**10.89** *(0)*	**-1.98**	**8.68** *(0)*	**10.89** *(0)*	**-2.21**
	0.1		min	8.66	10.89	-2.23	8.46	10.89	-2.43
	0.1		stddev	0.08	0.00	0.08	0.08	0.00	0.08
error free				**20.34**	**20.55**	**-0.21**	**26.10**	**26.64**	**-0.54**

Table 2: PSNR [dB] results for *cafe*

woman				0.125 bpp			0.5 bpp		
	ber	length		NTNU	VM0	gain	NTNU	VM0	gain
burst	0.001	1	max	26.89	22.95	3.94	32.37	22.65	9.72
	0.001	1	**mean**	**25.99** *(0)*	**20.84** *(0)*	**5.15**	**29.62** *(0)*	**19.96** *(1)*	**9.66**
	0.001	1	min	20.98	13.11	7.87	22.76	12.99	9.77
	0.001	1	stddev	1.39	2.01	-0.62	3.04	2.19	0.85
	0.001	10	max	26.91	26.99	-0.08	32.58	26.10	6.48
	0.001	10	**mean**	**26.35** *(0)*	**24.45** *(0)*	**1.90**	**32.09** *(0)*	**23.53** *(0)*	**8.56**
	0.001	10	min	18.58	17.97	0.61	19.91	15.96	3.95
	0.001	10	stddev	1.71	1.39	0.32	1.54	1.91	-0.37
	0.01	1	max	25.02	19.58	5.44	26.02	19.30	6.72
	0.01	1	**mean**	**20.81** *(0)*	**14.84** *(3)*	**5.97**	**21.42** *(0)*	**14.44** *(1)*	**6.98**
	0.01	1	min	17.17	10.78	6.39	17.24	12.09	5.15
	0.01	1	stddev	1.73	2.55	-0.82	1.73	2.37	-0.64
	0.01	10	max	26.73	22.91	3.82	31.25	22.40	8.85
	0.01	10	**mean**	**24.20** *(0)*	**20.23** *(0)*	**3.97**	**26.84** *(0)*	**19.36** *(0)*	**7.48**
	0.01	10	min	16.71	12.09	4.62	15.67	12.09	3.58
	0.01	10	stddev	2.93	2.72	0.21	4.33	2.68	1.65
BSC	0.001		max	24.19	18.70	5.49	26.64	18.47	8.17
	0.001		**mean**	**20.50** *(0)*	**14.94** *(1)*	**5.56**	**20.88** *(0)*	**14.32** *(0)*	**6.56**
	0.001		min	16.47	12.09	4.38	17.05	12.09	4.96
	0.001		stddev	1.57	2.18	-0.61	1.88	2.25	-0.37
	0.01		max	13.74	12.09	1.65	13.89	12.09	1.80
	0.01		**mean**	**12.73** *(0)*	**12.09** *(1)*	**0.64**	**12.57** *(0)*	**12.09** *(1)*	**1.48**
	0.01		min	11.71	12.01	-0.30	11.52	12.09	-0.57
	0.01		stddev	0.45	0.01	0.44	0.47	0.00	0.47
	0.1		max	9.85	12.09	-2.24	9.88	12.09	-2.21
	0.1		**mean**	**9.56** *(0)*	**12.09** *(0)*	**-2.53**	**9.50** *(0)*	**12.09** *(0)*	**-2.59**
	0.1		min	9.20	12.09	-2.89	9.17	12.09	-2.92
	0.1		stddev	0.14	0.00	0.14	0.15	0.00	0.15
error free				**26.91**	**27.47**	**-0.56**	**32.60**	**33.74**	**-1.14**

Table 3: PSNR [dB] results for *woman*

4.2 CE (SCQ/FLC) vs. baseline (TCQ/VLC)

Here (Tab. 4 to 6), the non-uniform scalar quantization has to compete with the baseline codec in which error resilience is integrated, i.e., using resynchronization markers, data partitioning, and error concealment. Due to time limitations, we used already existing codec software developed here at NTNU for the CE codec, instead of modifying the VM0 software to include nonuniform scalar quantization. However, our codec program uses the exact same filter bank and the same switches as specified in the VM0, so the results should not differ from what we would have obtained from a modification of the VM0.

Unfortunately, we did not have the time to produce several runs with different seeds for the CE codec. The PSNR values for the CE codec should thus be viewed as sample values instead of mean values. They are subject to a standard deviation comparable to that of the baseline runs, about 2.25 dB.

After transmission over noisy channels we get an average improvement in PSNR of about 6.5 dB over the baseline when comparing the sample values of the CE codec's PSNR with the mean values of the baseline codec's PSNR.

For the error-free case and in the average the CE codec performs 3.52 dB worse than the released baseline codec. However, it should be noted that the CE results for the rate 0.5 bpp are really too pessimistic. This is because we so far (again due to time limitations) only have included Lloyd-Max quantizers with up to four bits (16 levels) per quantizer. We really need up to 6-bit quantizers (64 levels) for the subblocks with the highest variance for the bit allocation to work optimally at such high rates. The 4-bit constraint thus severely restricts the achievable quality in the blocks with highest variance, especially in the error-free case. Quantization theory predicts an approximate PSNR gain of up to 6 dB per extra bit in those subblocks that are hit by this restriction.

bike				0.125 bpp			0.5 bpp		
	ber	length		baseline	CE	gain	baseline	CE	gain
burst	0.001	1	max	19.75			18.04		
	0.001	1	**mean**	**15.52** *(0)*	**22.36**	**6.84**	**14.75** *(0)*	**27.66**	**12.91**
	0.001	1	min	11.76			11.44		
	0.001	1	stddev	2.48			2.24		
	0.001	10	max	25.40			24.51		
	0.001	10	**mean**	**22.52** *(0)*	**20.95**	**-1.57**	**21.02** *(0)*	**27.97**	**6.95**
	0.001	10	min	13.17			13.12		
	0.001	10	stddev	2.33			2.32		
	0.01	1	max	14.55			14.43		
	0.01	1	**mean**	**11.24** *(0)*	**19.66**	**8.42**	**11.09** *(0)*	**22.19**	**11.10**
	0.01	1	min	10.88			9.85		
	0.01	1	stddev	0.65			0.37		
	0.01	10	max	18.82			17.76		
	0.01	10	**mean**	**15.41** *(0)*	**18.03**	**2.62**	**14.54** *(0)*	**23.10**	**8.56**
	0.01	10	min	11.76			11.41		
	0.01	10	stddev	2.46			2.24		
BSC	0.001		max	14.45			11.18		
	0.001		**mean**	**11.09** *(0)*	**22.11**	**11.02**	**10.99** *(0)*	**26.53**	**15.54**
	0.001		min	10.87			10.58		
	0.001		stddev	0.46			0.07		
	0.01		max	10.99			10.98		
	0.01		**mean**	**10.97** *(0)*	**18.51**	**7.54**	**10.97** *(0)*	**20.04**	**9.07**
	0.01		min	10.67			10.65		
	0.01		stddev	0.03			0.04		
	0.1		max	10.98			10.98		
	0.1		**mean**	**10.98** *(0)*	**10.76**	**-0.22**	**10.98** *(0)*	**11.02**	**0.04**
	0.1		min	10.94			10.94		
	0.1		stddev	0.01			0.01		
error free				**25.62**	**22.43**	**-3.19**	**32.56**	**26.60**	**-5.96**

Table 4: PSNR [dB] results for *bike*

cafe				0.125 bpp			0.5 bpp		
	ber	length		baseline	CE	gain	baseline	CE	gain
burst	0.001	1	max	17.05			16.09		
	0.001	1	**mean**	**14.47** *(0)*	**19.84**	**5.37**	**13.77** *(0)*	**23.28**	**9.31**
	0.001	1	min	12.07			11.46		
	0.001	1	stddev	1.31			1.28		
	0.001	10	max	20.59			22.08		
	0.001	10	**mean**	**19.02** *(0)*	**19.37**	**0.35**	**19.24** *(0)*	**23.38**	**4.14**
	0.001	10	min	13.79			13.94		
	0.001	10	stddev	1.32			1.51		
	0.01	1	max	12.78			12.96		
	0.01	1	**mean**	**11.15** *(0)*	**18.68**	**7.53**	**11.04** *(0)*	**20.73**	**9.69**
	0.01	1	min	10.90			10.55		
	0.01	1	stddev	0.39			0.29		
	0.01	10	max	16.58			15.86		
	0.01	10	**mean**	**14.23** *(0)*	**17.92**	**3.69**	**13.68** *(0)*	**20.82**	**7.14**
	0.01	10	min	11.98			11.36		
	0.01	10	stddev	1.33			1.26		
BSC	0.001		max	12.40			11.15		
	0.001		**mean**	**10.97** *(0)*	**19.09**	**8.12**	**10.92** *(0)*	**22.99**	**12.07**
	0.001		min	9.04			10.69		
	0.001		stddev	0.30			0.06		
	0.01		max	10.90			10.90		
	0.01		**mean**	**10.88** *(0)*	**17.35**	**6.49**	**10.88** *(0)*	**19.15**	**8.27**
	0.01		min	9.25			10.54		
	0.01		stddev	0.17			0.06		
	0.1		max	10.90			10.90		
	0.1		**mean**	**10.90** *(0)*	**10.98**	**0.08**	**10.87** *(0)*	**10.88**	**0.01**
	0.1		min	10.90			10.54		
	0.1		stddev	0.00			0.09		
error free				**20.59**	**19.22**	**-1.37**	**26.69**	**23.98**	**-2.71**

Table 5: PSNR [dB] results for *cafe*

woman				0.125 bpp			0.5 bpp		
	ber	length		baseline	CE	gain	baseline	CE	gain
burst	0.001	1	max	23.73			22.76		
	0.001	1	**mean**	**18.87** *(0)*	**24.34**	**5.47**	**17.92** *(0)*	**28.36**	**10.44**
	0.001	1	min	12.49			12.33		
	0.001	1	stddev	4.51			4.31		
	0.001	10	max	27.44			28.88		
	0.001	10	**mean**	**25.29** *(0)*	**23.86**	**-1.43**	**25.21** *(0)*	**28.46**	**3.25**
	0.001	10	min	12.79			12.79		
	0.001	10	stddev	2.71			3.04		
	0.01	1	max	19.62			19.30		
	0.01	1	**mean**	**12.46** *(0)*	**21.42**	**8.96**	**12.28** *(0)*	**24.19**	**11.91**
	0.01	1	min	12.09			11.56		
	0.01	1	stddev	1.38			0.98		
	0.01	10	max	23.52			22.69		
	0.01	10	**mean**	**18.72** *(0)*	**21.00**	**2.28**	**17.86** *(0)*	**24.45**	**6.59**
	0.01	10	min	12.48			12.32		
	0.01	10	stddev	4.43			4.29		
BSC	0.001		max	12.39			12.38		
	0.001		**mean**	**12.13** *(0)*	**24.05**	**11.92**	**12.11** *(0)*	**27.40**	**15.29**
	0.001		min	11.86			12.07		
	0.001		stddev	0.08			0.06		
	0.01		max	12.09			12.09		
	0.01		**mean**	**12.08** *(0)*	**20.76**	**8.68**	**12.04** *(0)*	**21.48**	**9.44**
	0.01		min	11.68			9.90		
	0.01		stddev	0.04			0.24		
	0.1		max	12.09			12.09		
	0.1		**mean**	**12.09** *(0)*	**13.05**	**0.96**	**12.06** *(0)*	**12.94**	**0.88**
	0.1		min	12.08			11.55		
	0.1		stddev	0.00			0.10		
error free				**27.52**	**24.52**	**-3.00**	**33.78**	**28.91**	**-4.87**

Table 6: PSNR [dB] results for *woman*

4.3 CE (SCQ/FLC) vs. VM0 (using the imbedded scalar quantizer of the VM0)

This simulation (Tab. 7 to 9) compares the nonuniform scalar quantization mentioned above with the current version of the VM0 with the -*sq* option switched on. The TCQ is then skipped and a *uniform* scalar quantization is performed instead.

An average of 2.55 dB degradation has to accepted in the error-free case using CE instead of the VM0 with the -*sq* option. Again, this is really too pessimistic since this average includes the values from the 0.5 bpp experiment, where the quality is severely restricted due to the lack of 5- and 6-bit Lloyd-Max quantizers for the blocks with highest variance. However, after transmission over error prone channels, we still achieve an average improvement of 5.9 dB over the VM0 with uniform scalar quantization. Note that this result is still based on sample – not mean – values from CE runs, and is thus subject to a certain standard deviation.

bike				0.125 bpp			0.5 bpp		
	ber	length		VM0/SCQ	CE	gain	VM0/SCQ	CE	gain
burst	0.001	1	max	19.40			17.21		
	0.001	1	**mean**	**16.39** *(0)*	**22.36**	**5.97**	**15.54** *(0)*	**27.66**	**12.12**
	0.001	1	min	12.18			11.97		
	0.001	1	stddev	1.22			1.15		
	0.001	10	max	23.84			25.80		
	0.001	10	**mean**	**21.22** *(0)*	**20.95**	**-0.27**	**20.41** *(0)*	**27.97**	**7.56**
	0.001	10	min	13.96			12.92		
	0.001	10	stddev	1.45			2.31		
	0.01	1	max	14.97			14.41		
	0.01	1	**mean**	**12.39** *(0)*	**19.66**	**7.27**	**12.10** *(0)*	**22.19**	**10.09**
	0.01	1	min	10.97			10.97		
	0.01	1	stddev	1.21			1.10		
	0.01	10	max	18.49			17.58		
	0.01	10	**mean**	**15.86** *(0)*	**18.03**	**2.17**	**15.04** *(0)*	**23.10**	**8.06**
	0.01	10	min	10.97			10.97		
	0.01	10	stddev	1.68			1.49		
BSC	0.001		max	14.07			13.96		
	0.001		**mean**	**12.33** *(0)*	**22.11**	**8.78**	**12.03** *(0)*	**26.53**	**14.50**
	0.001		min	7.61			10.22		
	0.001		stddev	1.16			1.05		
	0.01		max	10.97			10.97		
	0.01		**mean**	**10.95** *(0)*	**18.51**	**7.56**	**10.95** *(0)*	**20.04**	**0.09**
	0.01		min	9.29			8.96		
	0.01		stddev	0.17			0.20		
	0.1		max	10.97			10.97		
	0.1		**mean**	**10.97** *(0)*	**10.76**	**-0.21**	**10.97** *(0)*	**11.02**	**0.05**
	0.1		min	10.97			10.97		
	0.1		stddev	0.00			0.00		
error free				**23.84**	**22.43**	**-1.41**	**32.86**	**26.60**	**-6.26**

Table 7: PSNR [dB] results for *bike*

cafe				0.125 bpp			0.5 bpp		
	ber	length		VM0/SCQ	CE	gain	VM0/SCQ	CE	gain
burst	0.001	1	max	16.21			15.81		
	0.001	1	**mean**	**14.36** *(0)*	**19.84**	**5.48**	**14.04** *(0)*	**23.28**	**9.24**
	0.001	1	min	10.89			11.88		
	0.001	1	stddev	1.11			0.82		
	0.001	10	max	19.54			20.73		
	0.001	10	**mean**	**17.87** *(0)*	**19.37**	**1.50**	**17.95** *(0)*	**23.88**	**6.03**
	0.001	10	min	11.84			12.64		
	0.001	10	stddev	1.52			1.24		
	0.01	1	max	12.89			12.96		
	0.01	1	**mean**	**11.64** *(0)*	**18.68**	**7.04**	**11.59** *(0)*	**20.73**	**9.14**
	0.01	1	min	10.89			10.89		
	0.01	1	stddev	0.62			0.58		
	0.01	10	max	16.17			15.58		
	0.01	10	**mean**	**13.82** *(0)*	**17.92**	**4.10**	**13.78** *(1)*	**20.82**	**7.04**
	0.01	10	min	10.89			10.89		
	0.01	10	stddev	1.41			1.08		
BSC	0.001		max	12.76			12.30		
	0.001		**mean**	**11.69** *(0)*	**19.09**	**7.40**	**11.56** *(0)*	**22.99**	**11.43**
	0.001		min	10.89			10.89		
	0.001		stddev	0.55			0.51		
	0.01		max	10.89			10.89		
	0.01		**mean**	**10.89** *(0)*	**17.35**	**6.46**	**10.89** *(0)*	**19.15**	**8.26**
	0.01		min	10.89			10.89		
	0.01		stddev	0.00			0.00		
	0.1		max	10.89			10.89		
	0.1		**mean**	**10.89** *(0)*	**10.98**	**0.09**	**10.89** *(0)*	**10.88**	**-0.01**
	0.1		min	10.89			10.89		
	0.1		stddev	0.00			0.00		
error free				**19.54**	**19.22**	**-0.32**	**26.63**	**23.98**	**-2.65**

Table 8: PSNR [dB] results for *cafe*

woman				0.125 bpp			0.5 bpp		
	ber	length		VM0/SCQ	CE	gain	VM0/SCQ	CE	gain
burst	0.001	1	max	22.97			22.62		
	0.001	1	**mean**	**20.52** *(0)*	**24.34**	**3.82**	**20.13** *(0)*	**28.36**	**8.23**
	0.001	1	min	13.18			12.99		
	0.001	1	stddev	2.45			2.24		
	0.001	10	max	26.50			27.34		
	0.001	10	**mean**	**24.13** *(0)*	**23.86**	**-0.27**	**23.53** *(0)*	**28.46**	**4.93**
	0.001	10	min	17.97			15.96		
	0.001	10	stddev	1.29			1.94		
	0.01	1	max	19.58			19.30		
	0.01	1	**mean**	**14.52** *(0)*	**21.42**	**6.90**	**14.54** *(0)*	**24.19**	**9.65**
	0.01	1	min	12.09			12.09		
	0.01	1	stddev	2.43			2.40		
	0.01	10	max	22.92			22.60		
	0.01	10	**mean**	**20.20** *(0)*	**21.00**	**0.80**	**19.35** *(0)*	**24.45**	**5.10**
	0.01	10	min	12.09			12.09		
	0.01	10	stddev	2.73			2.70		
BSC	0.001		max	18.44			17.13		
	0.001		**mean**	**14.83** *(0)*	**24.05**	**9.22**	**14.28** *(0)*	**27.40**	**13.12**
	0.001		min	12.09			12.09		
	0.001		stddev	2.17			2.08		
	0.01		max	12.09			12.09		
	0.01		**mean**	**12.09** *(0)*	**20.76**	**8.67**	**12.09** *(0)*	**21.48**	**9.39**
	0.01		min	12.03			12.09		
	0.01		stddev	0.01			0.00		
	0.1		max	12.09			12.09		
	0.1		**mean**	**12.09** *(0)*	**13.05**	**0.96**	**12.09** *(0)*	**12.94**	**0.85**
	0.1		min	12.09			12.09		
	0.1		stddev	0.00			0.00		
error free				**26.50**	**24.52**	**-1.98**	**31.59**	**28.91**	**-2.68**

Table 9: PSNR [dB] results for *woman*

Figure 1: Error free case, **FLC**

5 Subjective Evaluation

Here only the two most representative samples of the comparison of the SCQ codec to the current VM0 are shown. The image *bike* is considered, with a bit rate of 0.5 bpp, first for the error free case (Fig. 1 and 2) and second, after transmission over a BSC with a BER of 0.001 (Fig. 3 and 4).

Figure 2: Error free case, **VLC**

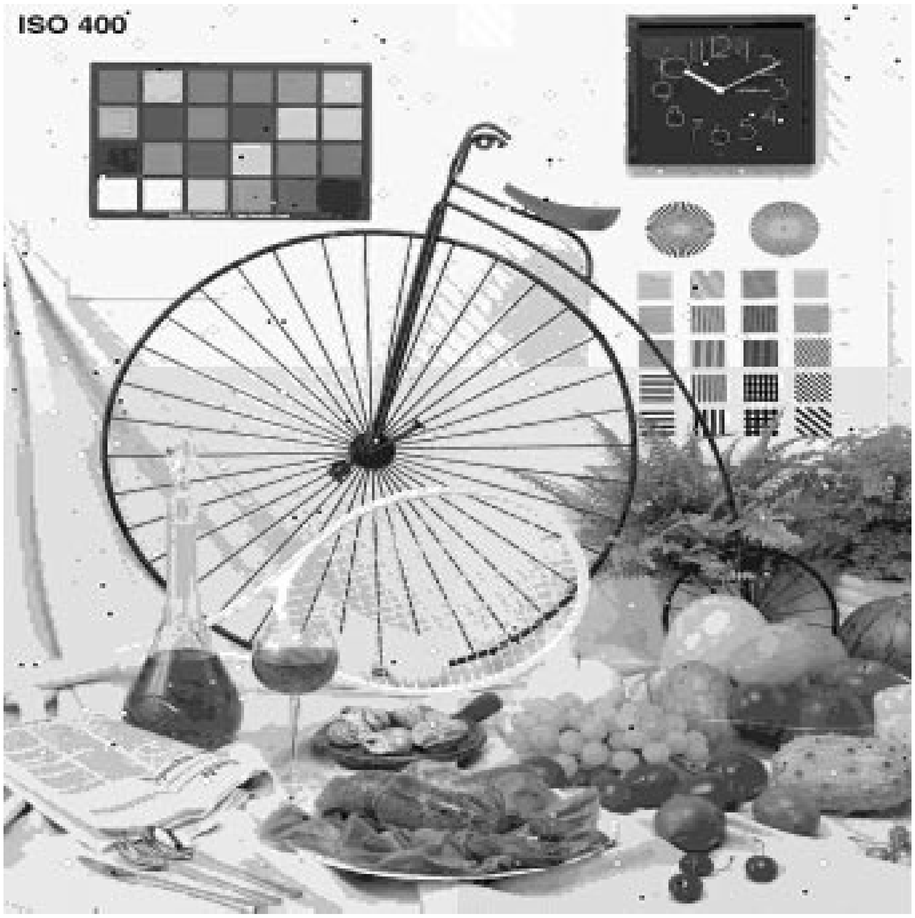

Figure 3: BSC, 0.001 BER; **FLC**

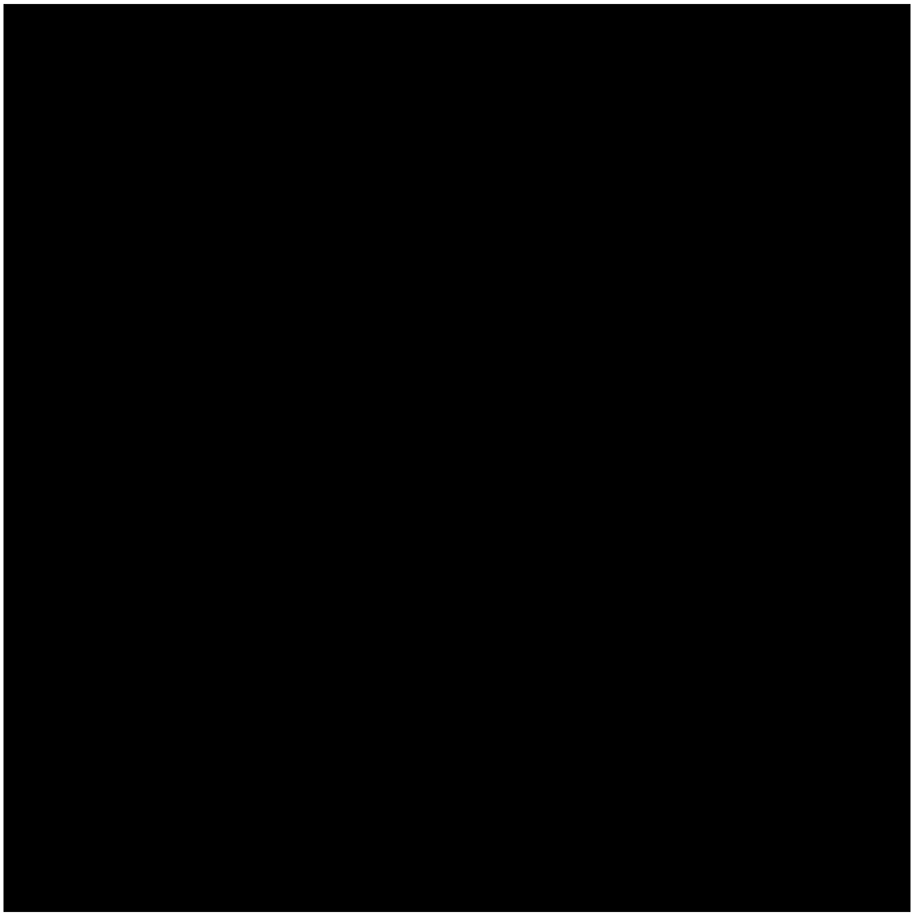

Figure 4: BSC, 0.001 BER; **VLC**

6 Conclusions

We have demonstrated the use of a simple fixed-length coding algorithm for possible use in the JPEG2000 profiles where images are to be transmitted in noisy environments. The algorithm replaces the TCQ/variable-length (arithmetic) coding currently used in the VM0 by *nonuniform scalar quantization with block-wise bit allocation in the wavelet domain.* The nonuniformity of the quantization characteristics, which are optimized with respect to Laplacian densities, results in approximately equiprobable fixed-length codewords, and hence eliminates the need for subsequent variable-length entropy coding. The main advantage is that each bit error now only affects the value of *one* wavelet coefficient, so the coder is very robust towards channel errors. It performs significantly better than both the VM0 with TCQ, resynchronization, and data partitioning both over binary symmetric and burst channels (about 6.5 dB gain on the average over all runs), and the VM0 with scalar uniform quantization (about 5.9 dB gain on the average). Also, the complexity is low compared to the TCQ solution. The disadvantage is that the coding efficiency is reduced relative to the VM0 in the error-free case – although not as much as our results would seem to indicate (Lloyd-Max quantizers with more than 16 levels should be included for use in blocks with high variance). Hence, fixed-length nonuniform scalar quantization should probably be considered as the method of choice only for applications where the error-free case is of no practical interest, such as wireless and mobile image communication.

We have also demonstrated the use of fixed-length coding using PVQ (Pyramidal Vector Quantization) and compared this *NTNU codec* to the VM0 using TCQ. The results show that the NTNU codec is also very robust, with an average gain during lossy transmission of 4.8 dB over the VM0 with TCQ, and graceful degradation. The loss of coding efficiency in the error-free case is in this case less than 1 dB on the average. However, the PVQ represent a more radical departure from the VM0 implementationwise than the nonuniform scalar quantization codec.

7 List of Abbreviations

AC	Arithmetic Coder
BER	Bit Error Rate
BP	Bit Plane
BSC	Binary Symmetric Channel
CE	Core Experiment
DWT	Discrete Wavelet Transform
FLC	Fixed Length Coding
HP	High Pass
LP	Low Pass
MSE	Mean Square Error
PSNR	Peak Signal-to-Noise Ratio
PDF	Probability Density Function (pdf)
R-S	Rate-Distortion
SCQ	Scalar Quantization
TCQ	Trellis Coded Quantization
VLC	Variable Length Coding
VM0	Verification Model 0

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