

ELECTRICAL ENGINEERING

Image Compression Scheme Using Improved Basic-LAVQ and Optimized VLC

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Abstract. In this paper, a predictive locally adaptive vector quantization (PLAVQ) for real-time image compression is developed and simulated. It is a hybrid of improved predictor, LAVQ and (VLC). The latter is a combination of Laplacian quantizer, Huffman coding, and optimum-modified B1-code for encoding the codewords and indices, respectively. Simulation shows that an improvement in speed of about 76% can be achieved with about 1.1 dB increase in the peak signal-to-noise ratio (PSNR) at the same bit rate. Optimization of the modified B1-code decreases the bit rate with an average of 37% for the same image quality. Simulation data of PSNR and bit rate vs. error threshold can be expressed by a decaying exponential model independent of image type.

Introduction

Simple vector quantization (VQ) is a generalization of PCM (scalar quantization) where a block of sequence of (k) continuous samples (vectors) is mapped (quantized) into a digital sequence. Because of its high performance at low bit rate, ease of implementation, and its inherent ability to exploit the high correlation between the neighboring pixels; (VQ) has been receiving great importance in the field of data compression. Vector quantization is essentially a pattern matching technique between input vectors x_i and set of vectors x_m in look-up table (codebook). The best possible match is extracted to represent the input vector pattern by a reproduction code vector and an index (m) [1].

Classic (VQ) can be regarded as a block of encoder and decoder which views the input x_1 and generates quantized output vector (\hat{x}_1) and an index (m) [2]. A typical monochrome image has a resolution (r) of 8 bits/pixel (bpp) and the goal of a (VQ) is to compress the image to a resolution < 1 bpp with same image quality. However, there are problems associated with the classical (VQ); *e.g.* (1) sensitivity to channel errors, (2) inefficient reconstruction of edge vectors, (3) large storage of codebook, (4) sub-optimality (for example, the LBG algorithm can easily be trapped in one of the local minima of the distortion surface), (5) large encoding complexity in time and space [2-5]. The computational complexity - in both time and space - increases linearly with the codebook size (N) and exponentially with the dimension (k), *i.e.* with kN , where $N = 2^{rk}$ [6;7].

To overcome these problems, some variations of (VQ) and combination with conventional image coding has been proposed in the literature. One way is to utilize the strongest properties of inter-vector or inter-block correlation of the image. This can be achieved through predictive (VQ) technique which is a vector extension of (DPCM). Also improved coding is possible by employing adaptive (VQ) where the codebook (or encoding rule) is changed slowly with respect to vector rate in time or space to suit the local statistics of input vector sequence. Complexity reduction and robustness against channel mismatch using channel-matched multistage VQ was theoretically demonstrated by Phamdo, *et al.* [3]. Transform (VQ) is computationally complex yet it has several advantages over spatial (VQ), Predictive (VQ) and hybrid DPCM. For Spatial (VQ), the effect of channel noise has not yet been investigated [2]. To reduce the edge degradation in the reproduced image, King and Ra [8] modified the conventional self-organizing map algorithm for 4×4 (VQ). A 3-layer address VA (AVQ) is introduced by Nasrabadi and Feng [9] which exploits the inter-block as well as inter-color correlations. A standard (VQ) codebooks in the first layer was used while the other two codebooks have codevectors consisting of the addresses of the previous layer codebook. Bit rate of 0.23 bpp and 0.35 bpp for monochrome and RGB image respectively were demonstrated.

A reduction in total bit rate of 0.125 bpp for an average rate of 0.516 bpp at an SNR of 39.53 dB was reported by employing Huffman coding of the address codevectors of moving image [10]. Ziv and Lampel [11] employed the concept of encoding future segments of the source-output via maximum length copying from a buffer containing the recent past output. It was shown, theoretically, that for given codeword length, the compression efficiency is comparable to that of an optimal variable-to-block codebook, but the algorithm is susceptible to channel error. A low-dimensionality (VQ) was used as a building block in predictive adaptive coding system, so that

the prediction error vector was coded by (VQ). Adaptation was achieved by a classifier to identify particular categories of speech statistics. An improvement of about 7dB in SNR over previous VQ and well competition with tree and trellis at the same bit rate was reported [12]. A reduction as low as 28% of total number of operation of those required by full search in (VQ) was reported using nearest neighbor search [6]. Continuation method (which is globally convergent and exhaustive) was applied with reduced execution time [13]. However, the execution time is about twice as that of LBG. To exploit inter-vector correlation an address-predicted VQ (APVQ) was introduced, where the address difference of the input and predicted vectors was encoded using Huffman code [14]. However, complexity and sensitivity to channel error were the shortcomings of (APVQ).

A combination of image-adaptive VQ (IAVQ) and variable length transform coding (VLTC) of the codeword solved the problem of overhead transmission and maintain the advantage of smaller codebook. Self-organized codebook and interblock correlation were also employed for further reduction of bit rate compared with (VLTC) up to 0.6 bpp [15]. Comparison of different algorithms for codebook design showed that simulating annealing algorithm (SA) produced the lowest distortion but required longer time, and depend on several parameters, while Pairwise nearest neighbor algorithm (PNN) is the fastest but the distortion is the highest [16]. There is no algorithm which could satisfy both low distortion and smaller CPU time criterion. The two main advantages of the locally adaptive VQ (LAVQ) [17] are fine-detailed representation and relatively high speed in codebook generation and encoding. However, the generated codebook is suboptimal resulting in inferior SNR- performance compared with LBG algorithm. The (LAVQ) can be considered a counterpart to the LBG algorithm as summarized in Table 1.

The Predictive LAVQ Algorithm

In the following section, a new dynamic vector quantization algorithm - called PLAVQ - is proposed and described. The PLAVQ is a hybrid of DPCM, an improved version of LAVQ, and variable length coding (VLC). The latter is a combination of Huffman coding and an optimization of modified B1-code (OPT. M-B1 Code) for further compression of the codewords and indices respectively. Figure 1 illustrates the overall configuration of the proposed algorithm, and in the following it is briefly explained.

The DPCM

The differential pulse code modulation (DPCM) is used to utilize the image redundancy and the high correlation between adjacent pixels to improve the SNR-bit

Table 1. Comparison of LBG & LAVQ algorithm

Algorithm	Relative speed	Image quality of		Codebook
		Detailed area	Smooth area	
LBT	Slow	Poor	Accurate	Optimized
LAVQ	Fast	Accurate	Poor	Sub-optimized

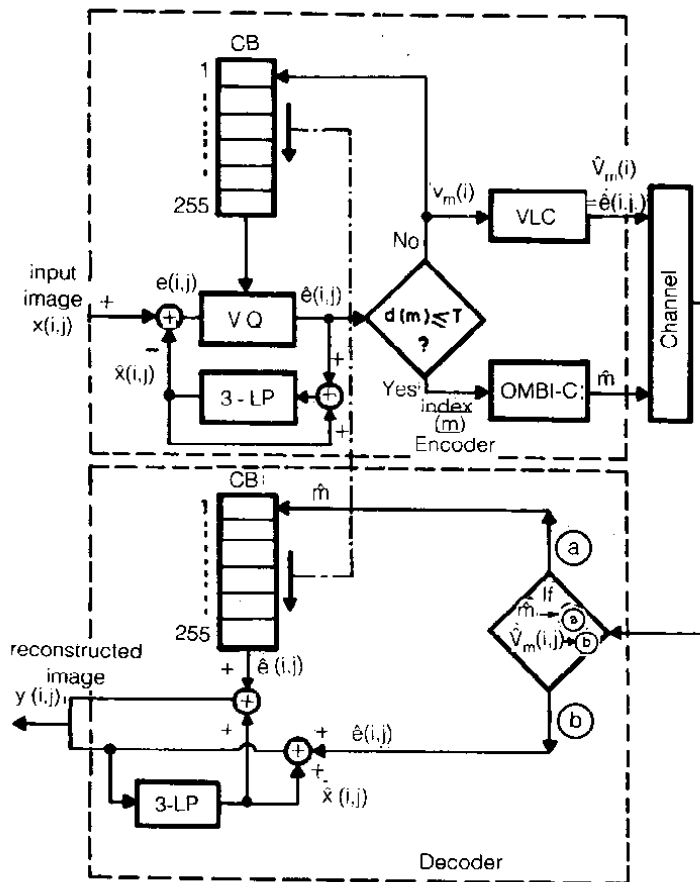


Fig. 1. Overall configuration of the proposed PLAVQ algorithm (refer to text for symbols).

rate performance. It has been shown [18] that for a linear predictor of order R , the prediction error and prediction gain vary as a function of R , and most of the prediction gain is realized with $R = 3$ after which the gain is saturated. The input image of size (N^2) undergoes DPCM using two-dimensions third-order linear predictor (3-LP) where predicted pixel $\hat{x}(i,j)$ is generated from a previous pixel on the same line $x(i,j-1)$ as well as the two neighbor pixels on the previous line, $x(i-1,j)$ and $x(i-1,j-1)$, *i.e.*:

$$\hat{x}(i,j) = b x(i,j-1) + c x(i-1,j) + d x(i-1,j-1) \quad (1)$$

The prediction coefficients b, c and d have to be optimized for minimum prediction error variance σ_e^2 , where the prediction error is given by:

$$e(i,j) = x(i,j) - \hat{x}(i,j) \quad (2)$$

Optimal values of $b = c = 0.52$ and $d = -0.52$ for 3rd order 2-D isotropic acf models; and $b = 0.746$, $c = -0.52$, and $d = 0.82$ for interframe predictor of 208×250 grid image has been used [18]. On the other hand, b, c , and d were chosen to be 0.5, 0.25, and 0.25, respectively for HDTV images [19], or were equal to (1/number of neighbor pixels) for HDTV signals [20].

Table 2. Effect of prediction coefficients on the PSNR for the tested images

b	Coefficient		Ref	Computed PSNR (dB)
	c	d		
0.746	-0.524	0.820	[18]	26.20
0.520	0.520	-0.058	[18]	26.75
0.500	0.250	0.250	[19]	27.72
0.333	0.333	0.333	[20]	27.54
0.500	0.300	0.200	This work	28.07

In this work, it is found that $b = 0.5$, $c = 0.3$, and $d = 0.2$ are optimal values as shown in Table 2. The reconstructed output pixels are given by:

$$y(i,j) = \hat{x}(i,j) + e(i,j) - q(i,j) \quad (3)$$

where $q(i,j)$ is the quantization error. The prediction error signal is used to generate the codebook of the (VQ). The elements of the codebook $e(i,j)$ is organized as an array of vectors of dimension $k = 8$ or 16 pixels.

The ILAVQ

In the basic LAVQ [17], full search for approximate matched codewords - stored in the codebook - with input vector is carried out. The approximation is governed by a choice of suitable threshold (or distortion allowance). If found, the index (m) of the codeword is sent while this codeword is pushed to the top of the codebook. If not found, a special index is sent followed by the vector itself, which becomes a new added codeword at the top of the codebook. All other codewords are pushed down the codebook. The same sequence occurs at the receiver so that the encoder and the decoder will have the same codebook at each matching step. In this research, vectors which fail the comparison test of absolute error to the square root of the minimum distortion are rejected resulting in complexity reduction. In this work, instead of full search, the improved version (ILAVQ) stops the search at minimum distortion threshold T . The matching method of vector is performed by calculating the pixel-wise distortion distance $d(m)$ as:

$$d(m) = \left\{ \sum_{i=1}^k \frac{[V(i) - V_m(i)]^2}{k} \right\}^{1/2} \leq T \quad (4)$$

where

- $V(i)$ = pixel value of image vector, $i = 1, 2, \dots, k$.
- $V_m(i)$ = pixel value of codeword vector.
- k = vector size (8 or 16 pixels).
- m = codeword index, $m = 1, 2, \dots, L$.
- L = codebook size (255 or 511 codewords).

If the test of $d(m) \leq T$ fails, the comparison is aborted and the next codeword is compared. Simulation comparison of the (ILAVQ) and the basic (LAVQ) showed that the relative reduction of execution time is about 62% to 88% for $T = 6$ to 18 respectively, with insignificant effect on bpp. Therefore, this improvement will result in faster search than the basic LAVQ.

Codebook compression

The codebook is a significant fraction of the total compressed image. Therefore, the use of lossless data compression of the quantized levels of the sent codewords and the indices of the codebook can enhance the bit rate performance without image quality degradation [21]. Therefore, a 28-level symmetric, non-uniform Laplacian quantizer is used to quantize the codebook vector. The discrete levels of the quan-

tizer output can be encoded by entropy coding to reduce the bit rate. This is carried out by means VLC procedures, such as Huffman codes [22], where highly probable levels are assigned shorter code bits.

Index compression

For each image vector, an index is sent whether it is of a matched codebook vector or a special index which tells the receiver that an image vector itself is transmitted. Since each index is sent as 8 or 9 bits (for 255 or 511 codebook respectively), then the bit rate (bit/pixel) is always ≥ 1 bpp for the LAVQ. Moreover, the percentage contribution of the indices in representing the reconstructed image is significant. For Lena monochrome image of size 512×512 pixels and 8 bpp resolution, the percentage can reach about 43% from the total bit rate for a threshold error of 10. Compression of indices will result in a further reduction in bit rate. B1-code [21] may be employed where a unique and shorter code than the binary index representation is assigned for each index. However, the B1-code becomes unuseful when it exceeds 8 bits, and bit rate reduction could not be achieved.

A modification of B1-code (MB1-Code) was employed [23] where a continuous (C) bit was included in each code, where $C = 0$ or 1 for odd and even locations respectively. The application of the MB1-Code as it is to this work does not reduce significantly the bit rate. This may be explained by the fact that the assignment of B1-code is based on the index order. Therefore, the MB1-codes are optimized for different images such as Lena, Truck and APC (USC-SIPI data base); by assigning the codes according to the probability occurrence of the indices of the codebook. Those indices with higher probability of occurrence are assigned fewer bits code and vice versa. Examples of the frequency of occurrence of codebook indices at $T = 14$ for the three images are depicted in Fig. 2, which indicates that optimization is in general, image dependent.

Table 3 shows the optimization of MB1-code of the 28 indices according to their probability of occurrence for Lena and at different threshold errors (T) as an example. The three different ranges of T ($0 \leq T \leq 6$, $6 < T \leq 10$, $10 < T \leq 20$) are quantized to $T = 6, 10, 14$; respectively. The improvement in the bit rate performance is found to be a reduction of about 0.4 bpp at the same PSNR due to the application of OPT. MB1-code, compared to the basic LAVQ. It is found that the reduction in transmitted indices is about 41.5%, 32.8%, 36.7% for $T = 6, 10, 14$; respectively due to index compression.

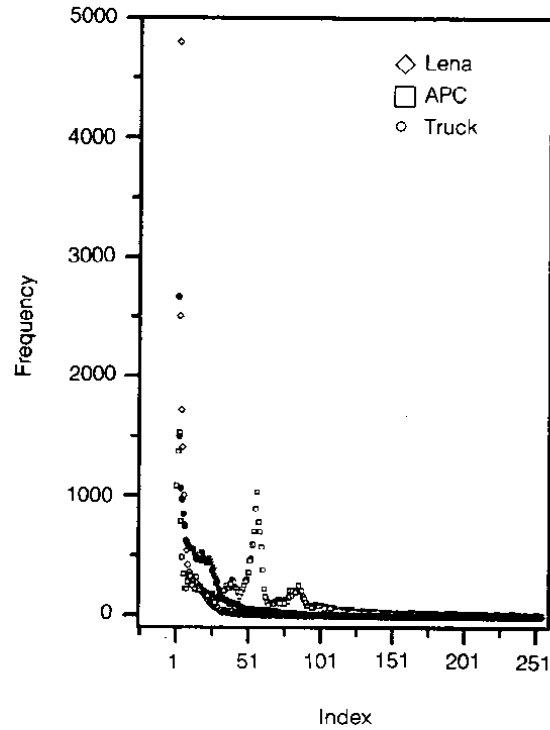


Fig. 2. Frequency of occurrence of codebook indices at $T = 14$ for Lena, APC and Truck.

Simulation Result

Simulations are carried out using PC IBM-486, 66MHz on the three monochrome images: Lena, Truck, and APC of 512×512 pixels size and 8 bpp resolution (USC-SIPI data base). The proposed algorithm is written in Visual Basic V-3. In the program the vector size can be set to either 8 or 16 pixel, the codebook size can be set to 255, or 511 codewords, and the threshold error T can be varied in the range $6 \leq T \leq 20$. The performance of the coding algorithm is evaluated by calculating the peak signal-to-noise ratio and bit rate (bpp) as follows:

$$\text{PSNR (dB)} = 10 \log_{10} \frac{(255)^2}{\text{MSE}} \quad (5)$$

where

$$\text{MSE} = \frac{1}{N^2} \sum_{i,j}^N [x(i,j) - \hat{x}(i,j)]^2 \quad (6)$$

Table 3. The optimization of B1-code assignment of indices according to their probability of occurrence for Lena at three different threshold error (T)

Indices for ranges of T			B1-Code	Bits
$0 < T \leq 6$ (T = 6)	$6 \leq T \leq 10$ (T = 10)	$10 < T \leq 20$ (T = 14)		
1	1	1	100	3
52	2	2	110	3
51	41	32	101	3
53	40	34	111	3
50	41	33	10000	5
54	44	3	11010	5
49	43	8	10001	5
2	39	36	11011	5
55	38	9	10100	5
48	37	31	11110	5
47	45	30	10101	5
56	3	0	11111	5
3	36	35	1000000	7
46	35	28	1101010	7
57	34	10	1000001	7
4	46	14	1101011	7
30	4	37	1000100	7
44	33	7	1101110	7
45	12	27	1000101	7
43	11	29	1101111	7
32	5	38	1010000	7
33	19	24	1111010	7
42	32	5	1010001	7
5	13	25	1111011	7
31	9	23	1010100	7
58	8	26	1111110	7
9	10	13	1010101	7
16	6	11	1111111	7

$x(i,j)$ = the (i,j)th pixel of input image,
 $\hat{x}(i,j)$ = the (i,j)th pixel of the compressed image,
 N^2 = image size, pixels.

and

$$\text{bpp} = \frac{(\text{Total bits sent})}{N^2} \quad (7)$$

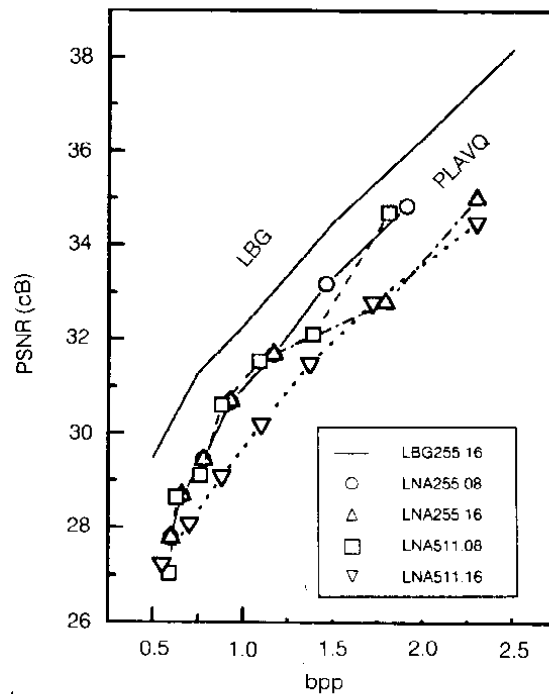


Fig. 3. PSNR vs. Bpp for Lena, using PLAVQ with different vector & code-book sizes, compared with LBG algorithm.

Figure 3 shows the PSNR vs. bit rate using the (PLAVQ) coding for different vector and codebook sizes, and the (LBG) result for comparison. It is shown that using vector size of 8 pixel results in better performance than using vector size = 16; and approximates that of LBG within about 1.1 dB for the same bpp.

Figure 4 depicts the relation between bit rate (bpp) and PSNR vs. threshold (T) as well as fitting models to the simulation data. It is found that, on the average of the tested images, the bit rate (bpp) decreases exponentially with the threshold (T) as;

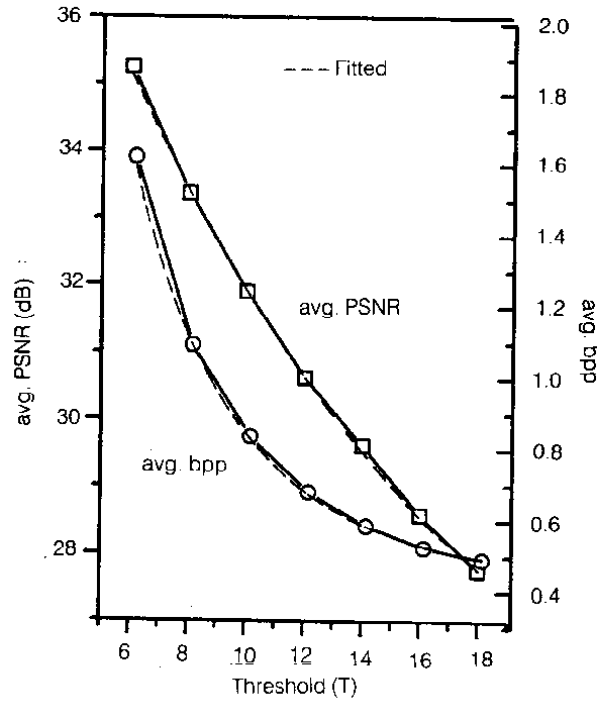


Fig. 4. Average PSNR & bpp vs. (T) for the tested images and their fitted models; for codebook = 255 entries and vector = 8 pixels.

$$\text{bpp}(T) = 0.47 + 1.15 \exp \left[-\frac{(T-6.0)}{3.46} \right] \quad (8)$$

The model can be used to deduce the suitable threshold for certain required bpp. Similarly, the average PSNR vs. threshold (T) can be expressed by a decreasing exponential model as:

$$\text{PSNR}(T) = 23.26 + 9.86 \exp \left[-\frac{(T-8.38)}{12.42} \right] \quad \text{dB} \quad (9)$$

Figure 5 shows the PSNR vs. bit rate performance for the tested images using PLAVQ with codebook = 255 and vector = 8 pixel. LBG performance is also shown for comparison. It is seen that the performance of the tested images be rated in descending order as APC > Truck > Lena, and the LBG is very near to PLAVQ for Truck image.

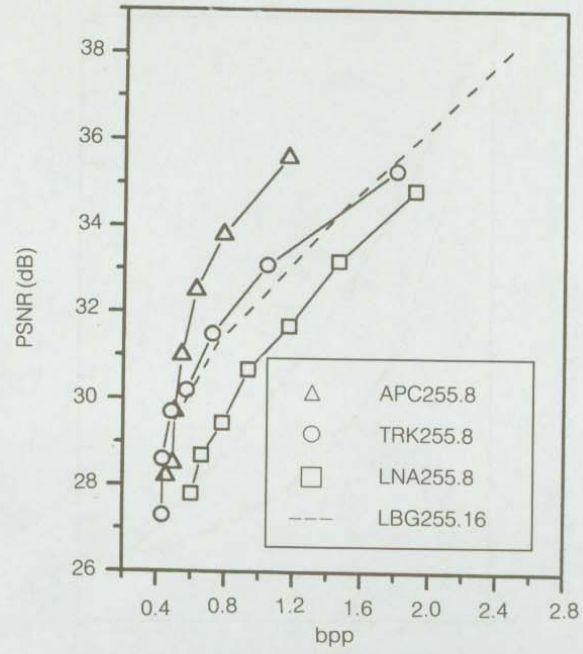
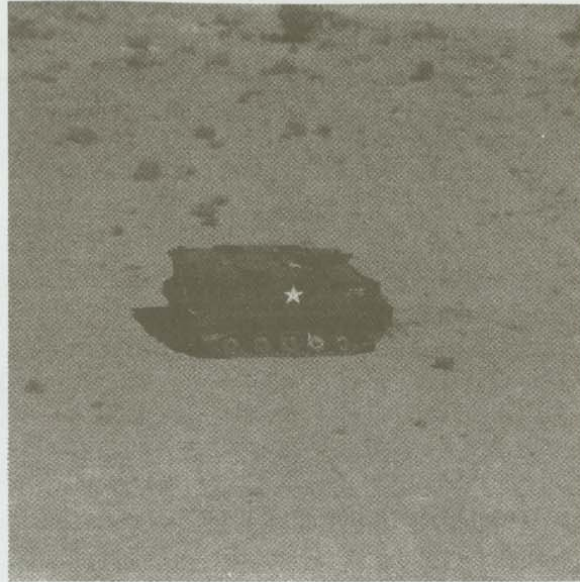


Fig. 5. PSNR vs. Bit rate performance for the tested images using code-book = 255 entries and vector = 8 pixels; compared with LBG.



(a)

Fig. 6.



(b)



(c)

**Fig. 6. APC image: a) original, b) reconstructed at bit rate of 1.16
bpp, c) reconstructed at bit rate of 0.61 bpp.**

Figure 6.a illustrates the original image of APC, while Fig. (6.b) and Fig. (6.c) illustrate the reconstructed image at bit rate of 1.16 bpp and 0.61 bpp, respectively. It is clear that the visual quality of the reconstructed images using PLAVQ are acceptable at low bit rate.

Conclusion

A new dynamic predictive, locally adaptive vector quantization (PLAVQ) algorithm is developed and implemented. It combines the advantages of adaptive predictive coding and lossless compression. It is shown that optimization of modified B1-code decreases the bit rate for the same image quality. Information can be transmitted at any desired bit rate with a pre-decided image quality. The PLAVQ is relatively fast and can be used for real-time transmission.

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خوارزم لضغط الصورة باستخدام (LAVQ) مُحسَّن و (VLC) أمثل

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ملخص البحث. في هذه المقالة، تم تطوير وتنفيذ خوارزم لتكمية متجه (VQ). وهذا الخوارزم تنبؤي وتكيفي محلي، وذلك لضغط الصور في الزمن الحقيقي. والخوارزم مكون من متبنيء مُحسَّن (LAVQ) و (VLC). وهذا الأخير عبارة عن جمع بين مُكَمِّم «لابلاسيان»، تشفير «هوفمان»، وشفرة B1 مطوّرة مثل (OMBI) وذلك لتشفير «كلمة الشفرة» والمؤشرات. وأظهرت المحاكاة أنه يمكن الحصول على تحسن في السرعة يبلغ حوالي ٧٦٪ بزيادة ١,١ ديسبل تقريباً في النسبة القصوى للإشارة إلى الشوشرة (PSNR) وعند معدل البتة نفسه. أما الشفرة B1 المطوّرة المثلّي فلقد أدت إلى نقص معدل البتة بحوالي ٣٧٪ في المتوسط، وعند جودة الصورة نفسها. وأوضحت المقالة أنه يمكن تمثيل العلاقة بين (PSNR) ومعدل البتة بدالة أسية متناقصة ولا تعتمد على نوع الصورة.