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Combining Modulation Diversity and Index Assignment to Improve Image VQ for a Rayleigh Fading Channel

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Abstract

Vector quantization (VQ) has been widely used in image coding systems. However, it is highly sensitive to channel errors, which may lead to very annoying blocking artifacts in the reconstructed images. In the present paper, modulation diversity (MD) is combined with index assignment (IA) by simulated annealing for improving image VQ for a Rayleigh fading channel: MD is used to reduce the bit error probability while IA is used as an attempt to reduce the visual impact of channel errors.

1. Introduction

The fundamental purpose of image compression is to reduce the number of bits to represent an image (while maintaining the necessary/acceptable image quality), in order to minimize the requirements of storage and transmission.

Vector quantization (VQ) plays an important role in many image coding systems, leading to high compression rates. However, when a communication system based on VQ involves transmission over a noisy channel, the performance of VQ may be seriously affected. Regarding VQ-based image transmission for a noisy channel, very annoying blocking artifacts may be introduced in the reconstructed images.

In recent papers, modulation diversity (MD) [1–3] has been successfully applied to improve the performance of wireless communication systems. In the present paper, considering VQ-based image transmission on a Rayleigh fading channel, it is shown that MD leads to reconstructed images with better quality when compared to the ones obtained without MD. It is also shown that an additional improvement may be obtained when an adequate codevector index assignment (IA) is carried out. In this paper, IA is obtained by simulated annealing.

The remaining of the paper is organized as follows. Vector quantization is briefly described in Section 2, with a focus on VQ for noisy channels. Section 3 describes the application of simulated annealing for index assignment. In Section 4 the modulation diversity is discussed. Section 5 describes the model of the communication system considered in the present work. In Section 6, simulation results are presented and discussed. Section 7 is devoted to the conclusions of the work.

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2. Vector Quantization

Vector quantization [4,5] can be defined as a mapping Q from a vector $\boldsymbol{x}$ in K-dimensional Euclidean space, $\mathbb{R}^K$, into a finite subset W of $\mathbb{R}^K$ containing N distinct reproduction vectors. Thus,

$$Q : \mathbb{R}^K \rightarrow W. \tag{1}$$

The codebook $W = \{\boldsymbol{w}_i;\ i = 1,\ 2,\ \ldots,\ N\}$ is the set of K-dimensional codevectors, also known as reconstruction vectors, template vectors or quantization vectors. From now on, $\boldsymbol{i}$ will be referred to as the index associated with codevector $\boldsymbol{w}_i$. Each index $\boldsymbol{i} \in \{0,1\}^b$ represents a b-bit binary word. The corresponding code rate of the vector quantizer, which measures the number of bits per vector component, is $R = \frac{1}{K}\log_2 N = \frac{b}{K}$. In voice waveform coding, R is expressed in bits/sample. In image coding, R is expressed in bits per pixel (bpp).

In a signal coding system based on vector quantization, the vector quantizer may be regarded as the combination of a VQ encoder and a VQ decoder. Given an input vector $\boldsymbol{x} \in \mathbb{R}^K$ from the source to be coded, the VQ encoder determines the distortion $d(\boldsymbol{x}, \boldsymbol{w}_i)$ between this source vector and each codevector $\boldsymbol{w}_i$, $i = 1,\ 2,\ \ldots,\ N$ from the codebook W. The optimum rule for coding is the nearest neighbor rule, by which the binary word $\boldsymbol{i}$ is transmitted to the decoder if codevector $\boldsymbol{w}_i$ corresponds to the minimum distortion, that is, if $\boldsymbol{w}_i$ presents the greatest similarity to $\boldsymbol{x}$ among all the codevectors in the codebook. In other words, the VQ encoder uses the encoding rule $C(\boldsymbol{x}) = \boldsymbol{i}$ if $d(\boldsymbol{x}, \boldsymbol{w}_i) < d(\boldsymbol{x}, \boldsymbol{w}_j), \forall j \neq i$. The task of the decoder is very simple: upon receiving the b-bit index $\boldsymbol{i}$, it simply looks up the codevector $\boldsymbol{w}_i$, from a copy of the codebook W, and outputs $\boldsymbol{w}_i$ as the reproduction (reconstruction) of $\boldsymbol{x}$. Therefore, it follows the decoding rule $D(\boldsymbol{i}) = \boldsymbol{w}_i$. The mapping of $\boldsymbol{x}$ into $\boldsymbol{w}_i$ is generally expressed as $\boldsymbol{w}_i = Q(\boldsymbol{x})$.

The mapping Q leads to a partition of $\mathbb{R}^K$ into N subspaces S_i, $i = 1,\ 2,\ \ldots,\ N$, for which

$$\bigcup_{i=1}^{N} S_i = \mathbb{R}^K \text{ and } S_i \cap S_j = \emptyset \text{ if } i \neq j, \tag{2}$$

where each cell or region S_i is defined as

$$S_i = \{\boldsymbol{x} :\ Q(\boldsymbol{x}) = \boldsymbol{w}_i\} = \{\boldsymbol{x} :\ C(\boldsymbol{x}) = \boldsymbol{i}\}. \tag{3}$$

2.1. VQ for Noisy Channels

Consider the communication system presented in Figure 1. The purpose of the system is to transmit a sequence of vectors $\boldsymbol{X} = \{\boldsymbol{x}\} \subset \mathbb{R}^K$ through a noisy channel by using VQ of the input vectors (source vectors) $\boldsymbol{x}$. Consider the transmission of the binary word $\boldsymbol{i} \in \{0,1\}^b$, with $b = \log_2 N$ bits, sent by the VQ encoder.

Figure 1: VQ for noisy channels.

If the channel introduces an error on the binary word $\boldsymbol{i}$, the VQ decoder will receive a binary word $\boldsymbol{j}$ that differs from $\boldsymbol{i}$, which was sent by the VQ encoder. Accordingly, the VQ decoder will not represent the input vector $\boldsymbol{x} \in \mathbb{R}^K$ by the codevector that obeys the nearest neighbor rule (vector $\boldsymbol{w}_i$, corresponding to the binary word $\boldsymbol{i}$). The VQ decoder will represent $\boldsymbol{x}$ by the codevector corresponding to the binary word $\boldsymbol{j}$. Thus, the output will be the reconstructed vector $\hat{\boldsymbol{x}} = \boldsymbol{w}_j$. Since $d(\boldsymbol{x}, \boldsymbol{w}_j) > d(\boldsymbol{x}, \boldsymbol{w}_i)$, it follows that the channel damages the quality of the reconstruction of $\boldsymbol{x}$.

Regarding image transmission for noisy channels, when a binary word corresponding to a codevector is corrupted by noise, a block of $K = K_1 \times K_2$ pixels is affected. Considering the transmission of the whole sequence of vectors (blocks of pixels) which composes an image, each binary word incorrectly received by the decoder will compromise the quality of the reconstruction of the vector (block of pixels) it corresponds to. As a consequence, in VQ of an image for a noisy channel, typical spurious annoying blocking artifacts, of $K_1 \times K_2$ pixels, may be introduced in the reconstructed image.

In the present paper, two techniques are applied to improve the quality of reconstructed images considering VQ for a Rayleigh fading channel. The first technique is modulation diversity (MD), addressed in Section 4. In the second one, known as robust vector quantization (RVQ), a codebook, which was previously designed for a noiseless channel, is subsequently made robust against channel errors by means of an index assignment algorithm [6, 7]. In the following, RVQ is briefly discussed.

Let $p_{\boldsymbol{X}}$ denote the K-dimensional probability density function of the source $\mathbf{X}$. Let p_i denote the *a priori* probability of vector $\boldsymbol{w}_i$ being selected as the reconstruction of $\boldsymbol{x}$ and let $p_{j|i}$, $i, j = 1, 2, \ldots, N$, denote the probability that the VQ decoder receives the index $\boldsymbol{j}$ given that index $\boldsymbol{i}$ was sent. Under the assumption that the mean-squared error distortion function is adopted (*i.e.*, $d(\boldsymbol{x}, \boldsymbol{w}_i) = ||\boldsymbol{x} - \boldsymbol{w}_i||^2$) and the centroid condition for the codevectors is satisfied, the overall distortion introduced by transmitting the vectors from source $\mathbf{X}$ through a noisy channel can be expressed as [6]

$$\begin{aligned} D = D_Q + D_C = &\sum_{i=1}^{N} \int_{S_i} p_{\boldsymbol{X}} ||\boldsymbol{x} - \boldsymbol{w}_i||^2 \, d\boldsymbol{x} \\ &+ \sum_{i=1}^{N} \sum_{j=1}^{N} p_i \, p_{j|i} ||\boldsymbol{w}_i - \boldsymbol{w}_j||^2. \end{aligned} \tag{4}$$

Since the quantization distortion D_Q does not depend on the channel (it depends only on the codebook design), making the vector quantizer robust to channel errors is equivalent to minimizing the channel distortion D_C. This can be accomplished by minimizing

$$I_{\text{dis}}(s) = \sum_{i=1}^{N} \sum_{j \in H^1(i)} ||\boldsymbol{w}_i - \boldsymbol{w}_j||^2, \tag{5}$$

where $\{j : j \in H^1(i)\}$ is the set of all binary words $\boldsymbol{j}$ for which the Hamming distance to $\boldsymbol{i}$ equals one, s is a particular codebook arrangement and $I_{\text{dis}}(s)$ is called disorder index of a codebook with arrangement s.

Let Π_N denote the set of all one-to-one functions $\pi : \{0,1\}^b \rightarrow \{0,1\}^b$. Each of the $N!$ bijections $\pi \in \Pi_N$ is called an index assignment function for the quantizer [7]. A permutation π uniquely maps each index $\boldsymbol{i} \in \{0,1\}^b$ to another index $\boldsymbol{i}' \in \{0,1\}^b$, where $\boldsymbol{i}' = \pi(\boldsymbol{i})$. A permutation may be seen as a reorganization or rearrangement of the codebook. Associated to a permutation π there is a unique (specific) codebook arrangement $\pi(s)$. As an example, consider the set of indexes $s = (0, 1, 2, 3, 4, 5, 6, 7)$, corresponding to the set of binary words $B = (000, 001, 010, 011, 100, 101, 110, 111)$. A new arrangement $s' = \pi(s)$ may be obtained by a permutation π such that the second binary digit of each codeword be inverted. That procedure leads to a new set of binary words $B' = (010, 011, 000, 001, 110, 111, 100, 101)$. That procedure is equivalent to have a set of indexes $s' = (2, 3, 0, 1, 6, 7, 4, 5)$ be represented by the binary words $(000, 001, 010, 011, 100, 101, 110, 111)$. In the example presented, the codebook was originally arranged such that codevectors $\boldsymbol{w}_0$, $\boldsymbol{w}_1$, $\boldsymbol{w}_2$, $\boldsymbol{w}_3$, $\boldsymbol{w}_4$, $\boldsymbol{w}_5$, $\boldsymbol{w}_6$ and $\boldsymbol{w}_7$ were identified by the binary words 000, 001, 010, 011, 100, 101, 110 and 111, respectively. A codebook rearrangement $\boldsymbol{w}_2$, $\boldsymbol{w}_3$, $\boldsymbol{w}_0$, $\boldsymbol{w}_1$, $\boldsymbol{w}_6$, $\boldsymbol{w}_7$, $\boldsymbol{w}_4$ and $\boldsymbol{w}_5$ was then obtained. In the codebook rearrangement $s' = \pi(s)$, codevector $\boldsymbol{w}_2$ is identified by 000, while in the original codebook arrangement s, that codevector was identified by 010. Considering the permutation π of the example presented, a "new" codebook (a reorganized codebook) W' was obtained: W' presents the same codevectors of W, but in a different order (arrangement, organization, configuration).

Regarding VQ for noisy channels, the target is to obtain an arrangement $s' = \pi(s)$ such that $I_{\text{dis}}(s') < I_{\text{dis}}(s)$. This corresponds to obtaining a codebook with arrangement s' that is more robust (less sensitive) to channel errors when compared to the original (initial) codebook with arrangement s.

Techniques for index assignment attempt to arrange the codebook such that the channel errors (which lead to the incorrect reception of the binary words sent by the VQ encoder) cause the incorrectly received codevectors (corresponding to binary words incorrectly received) to be close, on the average, to the intended codevectors. The search for the optimal codebook arrangement (corresponding to the optimal assignment of binary words to the codevectors) which leads to the best performance, involves a high computational complexity, since there are $N!$ possible configurations to be considered. As an example, a codebook with $N = 64$ reconstruction vectors has approximately 10^{89} different configurations to be investigated. In this sense, the index assignment problem for robust VQ may be classified as belonging to the class of NP-complete problems. Therefore, suboptimal optimizations techniques must be searched.

3. Simulated Annealing

The simulated annealing (SA) algorithm, which was introduced by Kirkpatrick *et al.* [8], has been successfully applied to many combinatorial optimization problems.

A typical combinatorial optimization problem seeks the minimum of a given nonnegative real-valued function. Generally, it consists of a set S of configurations or solutions and a cost function $C(\cdot)$ which determines for each configuration s the cost $C(s)$. For performing a search, one has to know the neighbors s' of each solution s, i. e., one has to define a neighbor structure $\mathcal{N}$ on S, such that $\mathcal{N}(s)$ determines for each solution s a set of possible transitions which can be proposed to s.

The fundamental idea behind SA is to add randomness to the search for the global minimum of the cost function, allowing the algorithm to occasionally avoid being trapped into local minima. A perturbation function, π, maps a system state (solution, configuration) s to another state $s' = \pi(s)$ according to some probability law. More precisely, in each step of SA, a new state is proposed and the resulting change in the cost function, $\Delta C = C(s') - C(s)$, is computed. If $\Delta C < 0$, the system moves to the new state $s' \in \mathcal{N}(s)$; however, when $\Delta C > 0$, the proposed state s' is accepted with probability $p = \exp(-\Delta C/t_m)$, and rejected with probability $1 - p$, where t_m denotes the temperature at the m-th algorithm step, with $0 < m < f$. The temperature is a nonnegative decreasing parameter of the SA algorithm. There are two ways to lowering the temperature t: a) if the number of the cost drops exceeds a prescribed number or b) if too many unsuccessful perturbations (which do not result in cost drops) occur. In the second case, the system reached a *thermal equilibrium state*. The rate at which t is reduced is called the temperature schedule of the annealing. In the present work, the exponential cooling schedule [8] was adopted. It is given by

$$t_m = t_0 \cdot \alpha^m, \tag{6}$$

where α is a positive constant less than unity.

The SA Algorithm can be summarized as follows:

Step 1) Initialization: Choose, randomly, the initial system state s and set $t = t_0$ as a sufficiently high temperature;

Step 2) Choose s' as a random perturbation of s;

Step 3) If $\{C(s') < C(s)\}$ then $s \leftarrow s'$, else

if $\{e^{-(C(s')-C(s))/t_m} >$ random$[0, 1]\}$ then $s \leftarrow s'$;

Step 4) If the number of cost drops exceeds a prescribed maximum number or if the number of unsucessfull perturbations is reached (thermal equilibrium), lower the temperature;

Step 5) If the temperature t is below the previously specified final temperture t_f or if the maximum number of iterations is achieved, stop. Otherwise, go to Step 2).

3.1. Application

The SA algorithm is applied for RVQ as follows:

- The configuration space S is defined as the set of all possible index arrangements, that is, it is the set of all possible orders in which the codevectors (reconstruction vectors) appear in the codebook. As an example, $s_1 = (0, 1, 2, 3, 4, 5, 6, 7)$ and $s_2 = (0, 1, 2, 3, 7, 6, 5, 4)$ are two possible configurations for a codebook with 8 codevectors;
- The cost function $C(s)$ is evaluated as the disorder index $I_{\text{dis}}(s)$ described by Equation 5;
- In the present work, the neighborhood $\mathcal{N}(s)$ of a specific configuration or state s is the set of all possible configurations s' obtained from s by randomly interchanging two indexes. As an example, $s' = (1, 0, 2, 3, 7, 6, 5, 4)$ can be produced by a perturbation in the state $s = (1, 0, 6, 3, 7, 2, 5, 4)$.

4. Modulation Diversity

Fading caused by multipath in wireless communication channels can significantly degrade the performance of digital communication systems. Many techniques have been proposed to improve the performance of those systems. Among them, one can mention: diversity techniques [9, 10] and coded modulation schemes [11].

The diversity techniques consist, basically, on providing replicas (redundancy) of the transmitted signals to the receiver. Typical examples of diversity techniques are: time diversity, frequency diversity and spatial diversity [10]. Another type of diversity has been recently proposed and is based on the introduction of redundancy by the combination of a suitable choice of the reference angle of an M-ary phase shift keying (MPSK) constellation with the independent interleaving of the symbol components before transmission [1, 3, 12]. In this work, this technique is called *modulation diversity*.

Consider the quadrature phase shift keying (QPSK) scheme, which can be seen as two binary PSK modulation schemes in paralell: one in phase and another in quadrature. The transmitted signal is given by [1]

$$\begin{aligned} s(t) =& A \sum_{n=-\infty}^{+\infty} a_n p(t - nT_S) \cos(\omega_c t) \\ &+ A \sum_{n=-\infty}^{+\infty} b_n p(t - nT_S) \text{sen}\,(\omega_c t), \end{aligned} \tag{7}$$

where

$$a_n, b_n = \pm 1 \quad \text{with the same probability,}$$

$$p(t) = \begin{cases} 1, & 0 \le t \le T_S \\ 0, & \text{otherwise,} \end{cases}$$

ω_c is the carrier frequency, A is the carrier amplitude and T_s is the signaling interval.

It can be seen from Equation 7 that the information transmitted in phase ($\cos(\omega_c t)$) is independent of the information transmitted in quadrature ($\text{sen}\,(\omega_c t)$). In the modulation diversity technique the introduction of redundancy in a QPSK scheme can be obtained by combining the judicious choice of the reference angle θ of the signal constellation, as shown in Figure 2, with the independent interleaving of the symbol components [1, 3]. Considering this rotated constellation, the transmitted signal can be rewritten as

$$
\begin{aligned}
s(t) = & A \sum_{n=-\infty}^{+\infty} x_n p(t - nT_S) \cos(\omega_c t) \\
& + A \sum_{n=-\infty}^{+\infty} y_{n-k} p(t - nT_S) \text{sen}\,(\omega_c t),
\end{aligned} \tag{8}
$$

where k is an integer which represents the time delay (expressed in number of symbols) introduced by the interleaving between the in-phase (I) and quadrature (Q) components. Moreover,

$$
x_n = a_n \cos\theta - b_n \text{sen}\,\theta \quad \text{and} \quad y_n = a_n \text{sen}\,\theta + b_n \cos\theta \tag{9}
$$

are the new QPSK symbols. The block diagram of the transmitter that implements this task is presented in Figure 3.

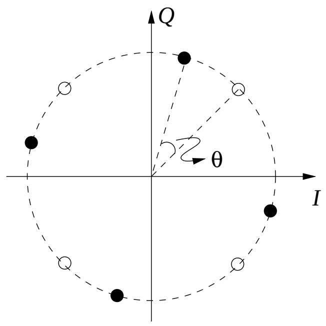


Figure 2: QPSK constellation: without rotation (∘); with rotation (•).

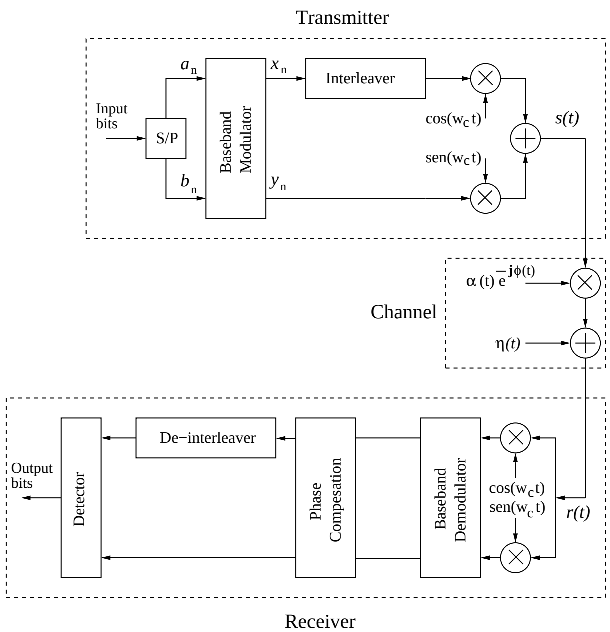


Figure 3: Block diagram of the communication system.

An interesting feature of modulation diversity is that the rotated constellation presents the same performance of a non-rotated one, when the signals are affected only by white Gaussian noise, because the Euclidean distance between the symbols does not depend on θ. Moreover, the spectral efficiency is not altered since two bits are transmitted for each signaling interval independently of θ.

5. The Communication System

Consider the communication system depicted in Figure 3. Assuming that the communication channel is characterized by fast fading, the received signal, denoted by $r(t)$, is given by

$$
r(t) = \alpha(t) e^{-j\phi(t)} s(t) + \eta(t), \tag{10}
$$

where $\eta(t)$ represents the additive noise, modeled as a complex white Gaussian process, with zero mean and variance $N_0/2$ by dimension, and $\phi(t)$ denotes the phase shift due to the channel, modeled as a random variable (r.v.) uniformly distributed in the interval $[0, 2\pi)$. Moreover, the multiplicative factor (fading amplitude) $\alpha(t)$ is modeled as a Rayleigh r.v.

At the receiver (Figure 3), $r(t)$ is baseband converted. The obtained signal $r_n(t)$ (low-pass equivalent) in the n-th signaling interval is

$$
r_n(t) = \alpha_n(t) e^{-j\phi_n(t)} s_n(t) + \eta(t), \;\; nT_s \le t \le (n+1)T_s, \tag{11}
$$

where $s_n(t)$ denotes the low-pass equivalent of the transmitted signal $s(t)$ and T_s is the signaling interval.

After the phase compensation (multiplication of $r_n(t)$ by $e^{j\phi_n(t)}$), the received signal in the n-th signaling interval, denoted by $\tilde{\boldsymbol{r}}_n$, can be expressed as

$$
\tilde{\boldsymbol{r}}_n = \alpha_n \boldsymbol{s}_n + \boldsymbol{\eta}_n, \tag{12}
$$

where $\boldsymbol{s}_n$ is the complex representation of the transmitted signal in the signaling interval nT_s, given by

$$
\boldsymbol{s}_n = x_n + j y_{n-k}. \tag{13}
$$

The elements of the complex signal $\boldsymbol{\eta}_n$ are independent and identically distributed (i.i.d.) Gaussian random variables with zero mean and variance $N_0/2$.

At the receiver, after deinterleaving (Figure 3) the received signal becomes

$$
\boldsymbol{r}_n = [\alpha_n x_n + \text{Re}\{\boldsymbol{\eta}_n\}] + j[\alpha_{n+k} y_n + \text{Im}\{\boldsymbol{\eta}_{n+k}\}], \tag{14}
$$

which is then processed using a symbol by symbol detection. In the previous Equation, Re$\{\boldsymbol{\eta}_n\}$ and Im$\{\boldsymbol{\eta}_{n+k}\}$ represent the real and imaginary parts of the noise $\boldsymbol{\eta}$ in signaling intervals nT_s and $(n+k)T_s$, respectively.

Assuming the transmission of equiprobable symbols, the optimum detector, based on the estimates of α_n, computes the Euclidean distance between the received signal and each constellation symbol (multiplied by estimates α_n and α_{n+k}) and choses the closest one to $\boldsymbol{r}_n$ as the received symbol.

Considering that the receiver is able to estimate without error the actual values of $\alpha(t)$ and $\phi(t)$ and that fading samples α_n and α_{n+k} are uncorrelated, it was shown in [2, 3] that the system bit error probability is minimized for $\theta = 27°$. The interested reader may find in [3] a performance analysis of modulation diversity taking into account the effects of channel estimation errors.

6. Results

This section presents simulation results concerning the transmission of the image Lena (256×256 pixels), presented in Figure 4, through a Rayleigh fading channel. Vector quantization with dimension $K = 16$ (corresponding to image blocks of 4×4 pixels) and codebook size (number of codevectors) $N = 256$ was considered. Hence, the corresponding code rate was $R = 0.5$ bpp. The codebook was designed by the algorithm LBG (Linde-Buzo-Gray) [13], using a tranining set consisting of four images 256×256. The quality of the reconstructed images was evaluated using the peak signal-to-noise ratio (PSNR).

Figure 4: Original Lena image (8.0 bpp).

The simulations involving modulation diversity consisted on using a QPSK scheme with a constellation rotation $\theta = 27°$, which is the optimun QPSK rotation angle according to [2, 3]. The transmission system used an interleaving depth k of 50 symbols.

Figure 5 presents the PSNR (more precisely the mean value of PSNR resulting from 200 image transmissions for each channel signal-to-noise ratio E_b/N_0 considered) of the reconstructed Lena image. The following notation was adopted:

- ORI: PSNR values obtained by using the original codebook arrangement (codebook without index assignment by simulated annealing) and considering a transmission system without modulation diversity ($\theta = 0°$);
- SA: PSNR values obtained by using the rearranged codebook (rearrangement provided by the simulated annealing index assignment) and considering a transmission system without modulation diversity ($\theta = 0°$);
- ORI+MD: PSNR values obtained by using the original codebook arrangement and considering a transmission system with modulation diversity ($\theta = 27°$);
- SA+MD: PSNR values obtained by using the rearranged codebook (simulated annealing index assignment) and considering a transmission system with modulation diversity ($\theta = 27°$).

Figure 5 shows that the substitution of the conventional scheme (ORI) by the modulation diversity scheme (ORI+MD) leads to a performance improvement in terms of PSNR of the reconstructed images, for all values of E_b/N_0 considered. As an example, it is observed that this substitution leads to a PSNR gain of 4 dB for E_b/N_0 =16 dB. Figure 5 also shows that the index assignment technique, obtained by simulated annealing (curve SA), outperforms ORI+MD for E_b/N_0 up to

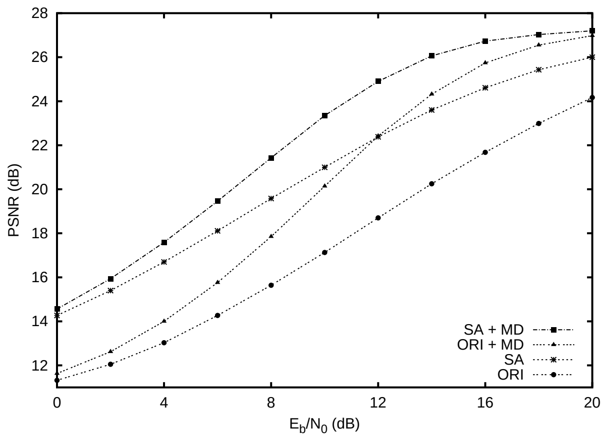


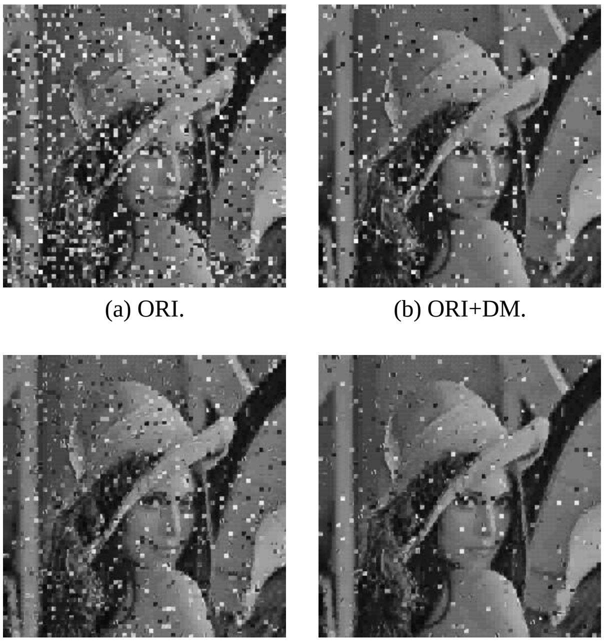
Figure 5: PSNR of the reconstructed Lena images as a function of the channel signal-to-noise ratio (E_b/N_0), considering a codebook with 256 codevectors.

12 dB. It is important to note that the best results in terms of PSNR are obtained when the transmission is carried out by combining modulation diversity and simulation annealing index assignment (SA+MD).

The quality gain in terms of PSNR of the reconstructed images obtained by using modulation diversity are due to the fact that modulation diversity leads to a decrease in the bit error probability of the communication system. Thus, modulation diversity leads to a reduction in the number of occurrences of errors between the binary words transmitted by the VQ encoder and the binary words received by the VQ decoder. This may be observed in Figures 6(a) and 6(b): it is observed that modulation diversity reduces the number of blocking artifacts in the reconstructed image. This is also observed by comparing Figures 7(a) and 7(b): the image corresponding to ORI+MD has a smaller number of spurious blocking when compared to image corresponding to ORI.

The PSNR gains obtained by substituting the original codebook by the codebook whose codevectors index assignment was obtained by simulated annealing comes from the following reason: when channel errors occur, the corresponding blocking artifacts introduced in the reconstructed image by using a rearranged codebood (SA index assignment) are less annoying when compared to the blocking artifacts by using the original (not submitted to SA index assignment) codebook. In other words, this comes from the fact that IA attempts to arrange the index of the codevectors such that the channel errors cause incorrectly received codevectors to be close, on the average, to the intended codevectors. Figures 6(a) and 6(c) (as well as Figures 7(a) and 7(c)) show that the blocking artifacts of the reconstructed image obtained by using the rearranged codebook (SA) are less annoying than the blocking artifacts of the reconstructed image obtained by using the original codebook (ORI).

Figures 6 and 7 show that the best image quality is obtained by SA+MD: MD reduces the number of blocking artifacts and, when blocking artifacts occur, index assignment by simulated annealing (SA) makes the corresponding visual impact be less perceptible.



(a) ORI. (b) ORI+DM.

(c) SA. (d) SA+DM.

Figure 6: Reconstructed Lena image (VQ with 0.5 bpp) after transmission through a Rayleigh fading channel with $E_b/N_0 = 8$ dB.

(a) ORI. (b) ORI+DM.

(c) SA. (d) SA+DM.

Figure 7: Reconstructed Lena image (VQ with 0.5 bpp) after transmission through a Rayleigh fading channel with $E_b/N_0 = 16$ dB.

7. Conclusions

A serious problem regarding the transmission of images on a VQ-based communication system is that VQ is highly sensitive to channel errors, which may lead to annoying blocking artifacts in the reconstructed images.

In this work, modulation diversity was used to reduce the bit error probability of the communication system, leading to a reduction in the number of blocking artifacts introduced in the reconstructed images. It was shown that an additional performance improvement is obtained if the image transmission is performed by using a rearranged VQ codebook, that is, a codebook submitted to an index assignment technique, which is used to reduce the visual impact of channel errors.

Modulation diversity consisted on introducing a rotation of $27°$ in the QPSK constellation used in the transmission system. Index assignment was performed by the simulated annealing algorithm. A Rayleigh fading channel was considered.

Visual inspections of the reconstructed images revealed the benefits of combining modulation diversity and index assignment.

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