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ADVANTAGES AND DRAWBACKS OF TWO-STEP APPROACH TO PROVIDING DESIRED PARAMETERS IN LOSSY IMAGE COMPRESSION

Abstract. The object of the study is the process of lossy image compression. **The subject of the study** is the two-step approach to providing desired parameters (quality and compression ratio) for different coders. **The goals of the study** are to review advantages of the two-step approach to lossy compression, to analyze the reasons of drawbacks, and to put forward possible ways to get around these shortcomings. **Methods used:** linear approximation, numerical simulation, statistical analysis. **Results obtained:** 1) the considered approach main advantage is that, in most applications, it provides substantial improvement of accuracy of providing a desired value of a controlled compression parameter after the second step compared to the first step; 2) the approach is quite universal and can be applied for different coders and different parameters of lossy compression to be provided; 3) the main problems and limitations happen due to the use of linear approximation and essential difference in behavior of rate/distortion curves for images of different complexity; 4) there are ways to avoid the approach drawbacks that employ adaptation to image complexity and/or use certain restrictions at the second step. **Conclusions:** based on the results of the study, it is worth 1) considering more complex approximations of rate-distortion curves; 2) paying more attention to adequate and fast algorithms of characterizing image complexity before compression; 3) using quality metrics that have quasi-linear rate/distortion curves for a given coder.

Keywords: lossy image compression; quality control; compression ratio; quality metric; two-step approach; advantages and drawbacks.

Introduction

The amount of images of different origin acquired by numerous imaging systems increases rapidly [1-3]. This happens in medical imaging [1], military applications [2], remote sensing [3], social networks [4], etc. Moreover, average image size increases due to better resolution of cameras and a tendency to use more image components in multispectral [5], hyperspectral [6], and radar polarization [7] imaging. This causes problems in acquired data management in general and image transfer via communication channels and storage in particular.

One way out is to compress images [5, 6, 8]. Lossless image compression techniques [8, 9] do not introduce distortions into compressed data but compression ratio (CR) for them is usually too small and this restricts their application in practice. Then, one has to apply lossy compression that introduces distortions inevitably [10, 11]. The questions that arise are what distortions can be considered appropriate, how to control them, what compression method to apply, and so on [11-13].

A standard tendency is that distortions become larger if CR increases [10, 12, 14] (the exceptions are the so-called strange images [15] that are met quite rarely and are not considered in this paper). This means that a rate/distortion curve, i.e. a dependence of a metric that describes distortions on a parameter that controls compression (PCC) is monotonous. This potentially allows reaching a compromise between compressed image quality and CR or to provide a desired quality characterized by a chosen metric [10, 12, 14]. Similarly, a desired CR can be provided as well [16-18] by this can be the expense of a certain reduction of compressed image quality.

Note that different practical situations and requirements to lossy image compression are possible. Providing a CR not smaller than a desired value is possible and JPEG2000-like coders are a good example of tools easily satisfying this requirement. Meanwhile, quality of compressed images in this case can differ a lot [12] and for some images (e.g., for complex structure ones) the quality can be not appropriate. In addition, providing a given CR is usually problematic for coders based on discrete cosine transform (DCT) [17], for example, a better portable graphics (BPG) encoder [16, 19]. Another typical priority of requirements is that it can be needed to provide a given quality of compressed images according to a chosen quality metric and other requirements are less important [20, 21]. Thus, the **object of our study** is the process of lossy image compression with providing a desired quality (characterized by some metric) or CR.

Additional requirements are possible. For example, a coder to be used can be pre-defined – it can be some standard such as JPEG [10] or JPEG2000 [18] or BPG [19] whilst the use of less known coders such as AGU [22] or advanced DCT coder (ADCT) [23] is also possible. A typical requirement could be also to provide a desired value of compression parameter quickly enough and with appropriate accuracy. This requirement needs explanation. Suppose that we should provide the peak signal-to-noise ratio PSNR of a compressed image of about 35 dB when introduced losses might be visible [15]. Experiments have shown that a given image compressed with, e.g., PSNR≈34.7 dB looks practically the same as the same image compressed with, e.g., PSNR≈35.3 dB. However, it is often possible to see the difference if a given image is compressed with, e.g., PSNR≈34.0 dB and PSNR≈35.0 dB. In other words, root mean square error (RMSE) of residual errors of providing a desired PSNR should be less than 0.15-0.2 dB (a more detailed study concerns the so-called just noticeable differences [24]). Similar studies have to be carried out for other than PSNR quality metrics to get a priori information on what is appropriate accuracy. The already performed studies show that there are “nonlinear” quality metrics [25] such as SSIM-based ones including MS-SSIM [26] and FSIM [27]. For them, the difference between two images compressed with FSIM equal to 0.99 and 0.98 is usually noticeable and between images compressed with FSIM equal, e.g., to 0.84 and 0.82 can be not noticeable.

These properties should be taken into account in design and analysis of methods (procedures, approaches) intended on providing the required quality. In this sense, one more aspect is the computational efficiency of compression and decompression. If a coder and decoder are not fast, then a fast procedure for providing a desired quality is extremely necessary [28]. This becomes clear from analysis of iterative procedures of providing a desired quality [12]. They presume image compression using a starting PCC and further decompression and quality metric calculation. Comparison of the calculated and desired values of the used metric allow determining the direction of PCC changing to “approach” the desired metric value. The iterative procedure stops when, after several iterations, the desired metric value is reached with appropriate accuracy. The problems of iterative procedures concern the number of iterations unknown in advance.

An alternative way deals with two-step procedure, which is the **subject of our study**. The basic idea is the following [16, 25, 28]. It is supposed that rate-distortion curves for different images behave similarly and are “locally parallel”. Then, it is possible to obtain an average rate-distortion curve using a representative set of test images in advance and, for a desired metric value, to determine a starting PCC value for the first step and the curve derivative for it. The first step involves image compression, decompression, and metric calculation for the starting PCC value. Then, the PCC value for the second step is determined using linear approximation for the desired and obtained (after the first step) metric values and the derivative value. This procedure has been quite successfully tested for several compression techniques and parameters to be provided [16, 25, 28] (see also [29] for more detail).

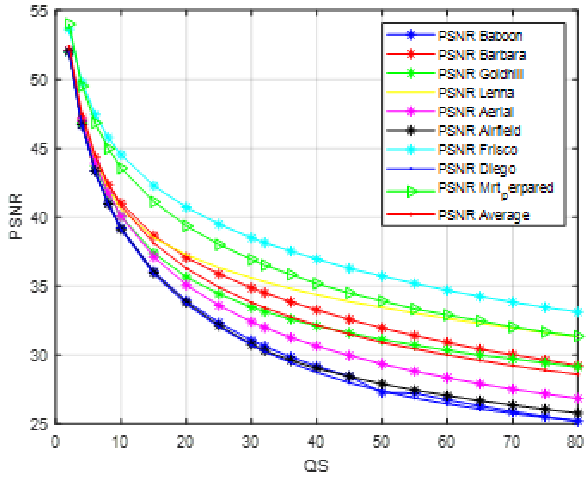
The goals of this paper are to review advantages of the two-step approach to lossy compression, to analyze the reasons of drawbacks, and to put forward possible ways to get around these shortcomings.

Background of the two-step approach and its basic properties

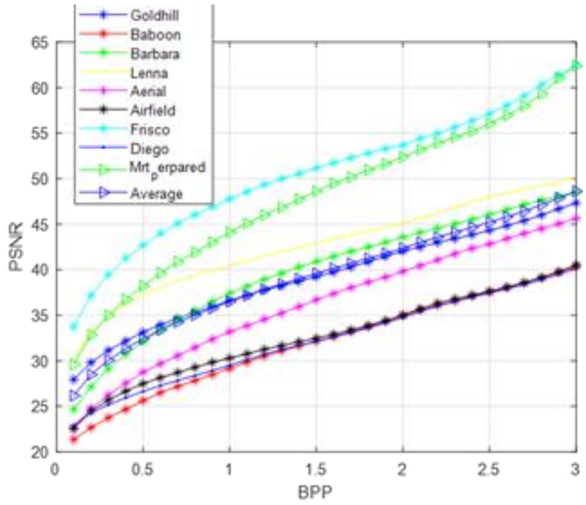
To get a better understanding, let us present two examples of rate/distortion curves. They are given in Fig. 1 as dependences of PSNR on quantization step (QS) that serves as PCC for the AGU coder and on BPP (bits per pixel, BPP=8/CR for 8-bit grayscale images) that serves as PCC for the SPIHT coder that can be treated as analog of JPEG2000.

Rate/distortion curves have been obtained for the sets of conventional test images listed in the plots. The average curves are presented in these plots as well.

Analysis of the rate-distortion curves in Fig. 1,a shows the following. First, we really deal with smooth monotonous dependences that can be locally interpolated and extrapolated well.



a



b

Fig. 1. Dependences of PSNR on QS for AGU (a) and on BPP for SPIHT (b)

Second, the dependences are individual and PSNR values for a given QS can differ a lot. For example, for QS=20, the difference between the maximal and minimal PSNR is 8 dB and it reaches 9 dB for larger QS. Meanwhile, the difference is of about 6 dB for QS=10. Third, the curves rarely intersect each other. This means that if PSNR for the image I1 is larger than for the image I2 for some QS1, it is quite probable that PSNR for the image I1 is greater that for the image I2 for QS2. Fourth, PSNR values (for a given QS) are larger for simpler structure images (such as Frisco) than for complex structure ones (such as Baboon or Diego). If one sets a fixed QS according the average curve (for example, QS=30 to provide PSNR≈35 dB), the provided PSNR for particular images vary in rather wide limits from ≈31 dB to ≈38 dB and this is not appropriate. This is just the motivation for using the two-step procedure and image compression using a corrected QS. Fifth, the derivative dPSNR/dQS for the average curve is not constant and its absolute value for a smaller QS (e.g., QS=10) is considerably larger than for a larger QS (e.g., QS=40).

Analysis of the curves in Fig. 1,b allows drawing the following conclusions. First, we again deal with smooth monotonous dependences (although this time the dependences are the increasing ones). Second, the dependences are individual and PSNRs for a given BPP differ considerably. For example, for BPP=1 (CR=8), PSNR value differ by 18 dB. Third, there are curves that intersect each other but the curves that are the “nearest” to each other behave in a very similar way. Fourth, similarly to the previous case, for a given BPP, the smallest PSNR values are observed for the test images having the most complex structure (Baboon and Diego). Fifth, the average curve is smooth but it is not linear (although it can be considered locally linear as well as the particular rate/distortion curves).

The results of this analysis show that linear approximation for the two-step procedure can be tried, at least for the cases of rate-distortion curves presented in Fig. 1. Recall that, at the first step, PCC_1 is set according to the average curve. For example, if one needs to provide $PSNR_{des}$=40 dB for the coder SPIHT, BPP_1 should be set equal to 1,6 (see Fig. 1,b). Then, after the first step, one obtains $PSNR_1$ in the limits from 32.5 dB (then, BPP_2 has to be increased for such images) till 52 dB (and BPP_2 should be decreased for them). The formula for calculating BPP_2 is the following:

$$BPP_2 = BPP_1 + \\ +\left(PSNR_{des} - PSNR_1\right) / \left(dPSNR/dBPP\left(BPP_1\right)\right) \quad (1)$$

or, more in general, for a considered metric (parameter) Metr:

$$PCC_2 = PCC_1 + \\ +\left(Metr_{des} - Metri_1\right) / \left(dMetr/dPCC\left(PCC_1\right)\right). \quad (2)$$

Let us present some data demonstrating improvement of accuracy in providing a desired quality of compressed images. For the SPIHT coder, the simulation results are given in the paper [30]. It is shown that mean squire error (MSE) of residual errors of providing PSNRs equal to 40 dB, 35 dB, and 30 dB has reduced by 12, 4, and 3 times, respectively, due to the second step. However, the residual errors can be of about 6-8 dB and this happens for images for which the rate-distortion curves are “the most distant” from the average rate/distortion curve, i.e. for the most simple and complex structure images.

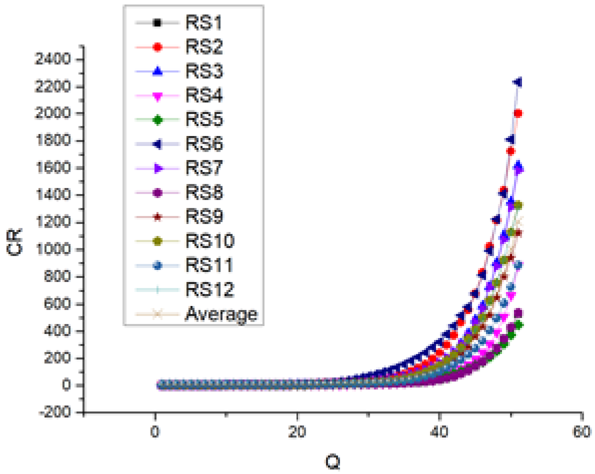
The analysis in [30] is also carried out for the visual quality metric PSNR-HVS-M where HVS relates to human vision system and M relates to masking. This metric (see https://ponomarenko.info/psnrhvsm.htm) takes into account two important peculiarities of HVS, namely, higher sensitivity to distortions in low spatial frequencies than in high spatial frequencies as well as masking effect. Analysis for PSNR-HVS-M shows that MSE of residual errors for this metric decreases by 6-40 times due to the second step and the largest errors are of about 2.5-3.5 dB. The examples for the SPIHT coder show both advantages and drawbacks of the two-step approach. On the one hand, the accuracy of providing the desired quality is substantially improved due to the second step. On the other hand, the achieved accuracy can be still not appropriate.

The analysis in the paper [31] performed for the AGU coder shows the following. The two-step approach performs well enough for $PSNR_{des} \geq 35$ dB providing MSE reduction by 4 and more times after the second step with maximal residual error of smaller than 3.6 dB. But even for $PSNR_{des}$=35 dB there are some problems arisen. First, there are images for which QS_2 differs from QS_1 essentially (by about two times). For example, for the test image Frisco, QS_1=24.6 ($PSNR_1$=39.6 dB) and QS_2=45.3 ($PSNR_1$=36.2 dB); for the test image Baboon, QS_1=24.6 ($PSNR_1$=32.5 dB) and QS_2=13.1 ($PSNR_1$=37.1 dB). In both cases, the accuracy has improved after the second step, but, according to visual inspection of the plots in Fig. 1,a, the curves can be hardly approximated by the first order polynomials in such wide intervals. Second, there are images, for which the absolute value of the residual error after the second step is larger than after the first step. For example, for the test image Airfield, QS_1=24.6 ($PSNR_1$=32.3 dB) and QS_2=12.2 ($PSNR_1$=38.6 dB). Third, most $PSNR_2$ values occurred larger than $PSNR_{des}$. In other words, the provided $PSNR_2$ are biased in statistical sense. This might be not a big problem since the provided quality is, on the average, better than desired. However, this happens by the expense of a smaller average CR, which is undesired.

The results [31] show that the main problems in providing $PSNR_{des}$ arise for $PSNR_{des}$<35 dB. For example, for $PSNR_{des}$=30 dB (which is typical for lossy image compression), there are images for which QS_2 and QS_1 differ by more than three times. For example, for the test image Diego, QS_1=60.1 ($PSNR_1$=26.4 dB) and QS_2=16.3 ($PSNR_1$=35.2 dB), i.e. no improvement in providing $PSNR_{des}$=30 dB is observed due to the second step. Moreover, for highly textural images, it happens that QS_2 calculated according to (1) occurs to be negative and this is unreal since QS can be only positive. Thus, the drawbacks of the basic two-step method could be the following: 1) it produces biased values of the considered metric (with respect to its desired value); 2) the PCC calculated according to (1), i.e. QS or BPP might have no physical sense.

It might seem that the presented examples relate only to PSNR. To show that these are the more common phenomena, consider the task of providing a desired CR [16]. Fig. 2 presents dependences of CR on parameter Q that serves as PCC for the BPG coder applied to color images (12 test remote sensing images have been analyzed) using the 4:2:0 format. Q varies from 1 to 51 and can be only integers. Fig. 2,a shows CR values for the entire range of Q and it is seen that, for large Q, CR can exceed 1000. Fig. 2,b presents more detailed data (for Q≤35) and, as one can see, CR can differ by more than ten times depending on image complexity. Thus, the task of providing a desired CR is important and sophisticated one.

The two-step approach has been applied to solve it for CR_{des} equal to 10, 20, 40, and 80. The obtained data are given in Table 1. Here, MSE_1 is MSE of the provided CR after the first step; MSE_2 and $MEAN_2$ are MSE and mean of the provided CR after the second step. Analysis of MSE_1 and MSE_2 shows that the two-step approach works well and radically increases accuracy (note that both MSE_1 and MSE_2 radically increase if CR_{des} increases). Meanwhile, the provided mean CR occurs to be smaller than desired and this might cause serious problems (in fact, it is needed to provide mean CR equal or slightly larger than CR_{des} since otherwise some images can be lost if a set of images has to be transferred via communication line with a limited bandwidth during a limited time).



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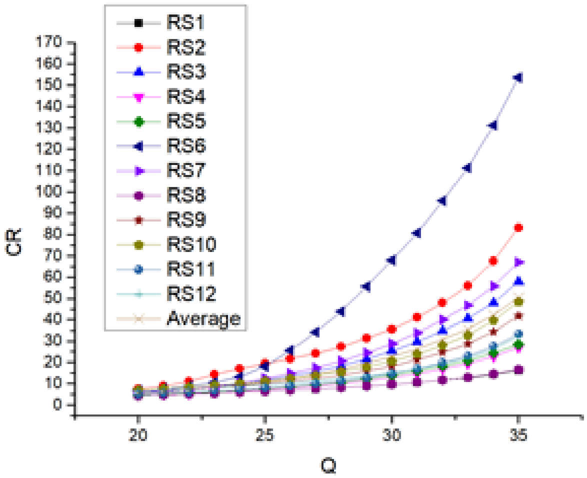


b

Fig. 2. Dependences of CR on Q for three-channel test images compressed by the BPG coder for Q from 1 to 51 (a) and from 1 to 35 (b), format 4:2:0

Table 1 – **Statistical results for the two-step approach for the BPG coder applied to color images, format 4:2:0**

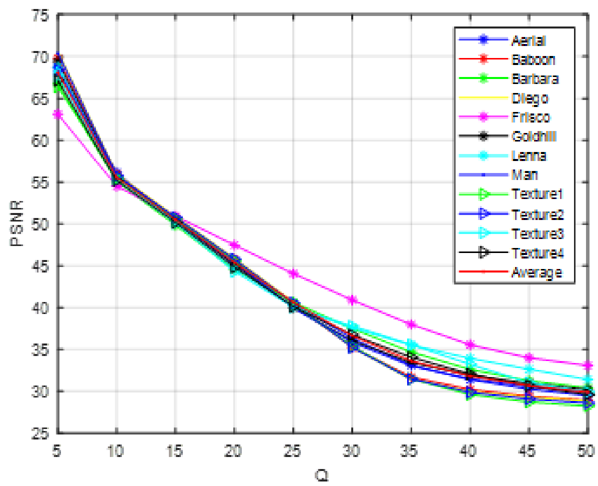
CR_{des}	MSE_1	MSE_2	$MEAN_2$
10	18.22	1.51	8.82
20	265.1	22.8	16.89
40	1.05×10^3	104.6	33.76
80	3.79×10^3	155.6	71.43

Note that in both cases of dependences in Fig. 1,a and 2 we deal with positive second derivative of particular and average curves. Then, for negative first derivative (Fig. 1,a), one gets positive bias of the provided PSNR whilst, for positive first derivative (Fig. 2), the negative bias is observed. This means the following.

First, the second derivative of dependences might play an important role in accuracy of the two-step approach. Second, this happens if PCC_2 and PCC_1 change considerably after correction (there are images for which CR_1 and CR_2 differ by several times [16]).

Third, it might be so that CR_1 is larger than CR_{des} and CR_2 is smaller than CR_{des} (and vice versa), i.e. “overcorrection” takes place.

One more problem with the two-step approach is that, for some coders, PCC values can be only integer. This takes place for JPEG for which quality factor serves as PCC and it can be integers from 1 (the worst quality) to 100 (ideal quality). The same holds for the BPG coder (see above). This means that PCC_1 and PCC_2 have to be rounded-off to the nearest integer. This causes additional errors. Fig. 3 shows dependences of PSNR and PSNR-HVS-M on Q for the BPG-coder applied to grayscale images. Analysis of these plots demonstrates obvious advantages of this coder. First, the rate/distortion curves go “compactly”, i.e. the difference in PSNR values for particular images for a given Q (e.g., Q=35, Fig. 3,a) is less than the difference for the AGU coder (see data for QS=38, Fig. 1,a) or SPIHT (see data for BPP=0.8, Fig. 1,b). Second, there is a large interval of Q, from Q=10 to Q=35), for which the curves behave almost linearly with PSNR reduction about 1 dB and PSNR-HVS-M reduction by 1.33 dB for Q changing by 1.



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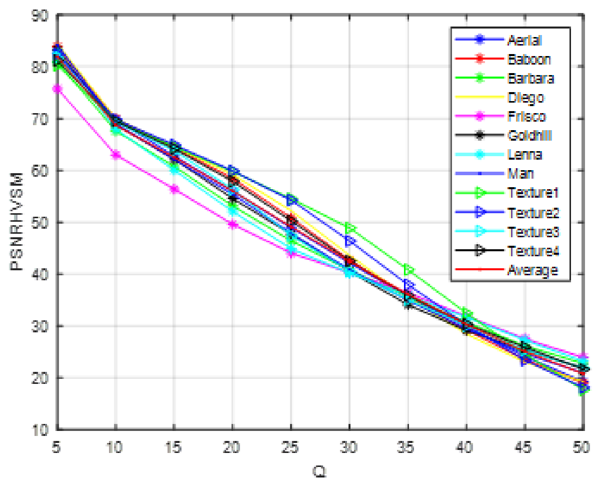

b

Fig. 3. Dependences of PSNR (a) and PSNR-HVS-M (b) on Q for the BPG coder

This allows setting Q_1 easily and obtaining Q_2 with providing high accuracy of the metric desired value [32].

As the result, for $PSNR_{des}$ equal to 40 dB, 35 dB, and 30 dB, MSE_1 equals to 1.2, 3.8, and 1.8 dB^2. In turn, MSE_2 is equal to 0.1, 0.2, and 0.8 dB^2, respectively. Thus, the provided accuracy is radically improved by the second step.

Besides, the provided accuracy is better than for the AGU and SPIHT coders. In some cases, MSE_2 approaches to potential limit that is equal to 1/12 dB^2 for PSNR under assumptions that the residual errors have uniform distribution due to discrete values of Q and PSNR changes by 1 dB for Q changing by 1.

Statistics of providing a desired PSNR-HVS-M is at the same order [32].

Ways to improve accuracy

Summarizing the observations in the previous Section, it is possible to state the following. The problems in two-step approach appear if:

1) the dependences of a metric on PCC (both particular dependences and the average one) are essentially nonlinear; this leads to bias in providing the desired parameters and even to "abnormal" values of PCC_2;

2) the dependences for particular images differ a lot (as in Fig. 1, b) and can be "far away" from the average curve; then the derivative estimated for the average curve can differ a lot from the derivative for a particular rate/distortion curve.

Concerning nonlinearity of dependences, several ways out are or seem possible.

First, it is possible to restrict variation limits of PCC at the second step, for example, to introduce some rules such as PCC_2 should not be smaller than $PCC_1/2$ and it should not be larger than $2PCC_1$. Such rules sufficiently improve the accuracy and allow avoiding "abnormal" values of PCC_2 [29].

Second, it is worth trying to use the second order polynomials in determining PCC_2 instead of linear approximation (2).

To our best knowledge, such trials have not been done yet.

Third, in some extreme cases when $Metr_2$ differs from $Metr_{des}$ considerably, it might be reasonable to perform the third step similarly to the second one.

Concerning significant difference in behavior of the rate/distortion curves, one way out has been already proposed [33].

At preliminary stage (off-line), average rate/distortion curves for simple, medium, and complex structure images are obtained.

At the stage of compressing a particular image, it is first analyzed using some simple algorithm and the considered image is referred to one of three aforementioned classes.

Then, the two-step procedure is applied using the corresponding average rate-distortion curve. Image entropy or some other features that can be calculated easily can be employed for image pre-classification. This direction needs further research since it is unclear how many classes to use, what is the best parameter (statistic) characterizing image complexity and so on. It seems that neural networks can be useful for efficient development of this direction.

Another option presumes the use of quality metrics that have more linear and compact dependences on PCC. Suppose that there are two or several visual quality metrics that are (approximately) equally good in characterizing quality of compressed images. For example, these can be metrics PSNR-HVS-M, FSIM [27], MDSI [34], PSIM [35], HaarPSI [36], etc.

Then, if one knows the main properties of these metrics (e.g., distortion visibility threshold), it is possible to choose a metric that has the most linear dependence on PCC for a given coder and the least "divergence" of rate/distortion curves for particular images. This idea has to be studied in the future.

Conclusions

In this paper, we have analyzed the advantages and drawbacks of the two-step approach to providing the desired values of compression parameters, compressed image quality according to different metrics in the first order.

It has been demonstrated that the two-step approach is often quite efficient - it allows providing accuracy by about one order of magnitude better after the second step compared to accuracy after the first step. However, there are practical cases where the approach does not perform perfectly.

This mostly happens if the average dependence is not linear (and, thus, linear approximation is not strictly valid) and/or if particular rate/distortion curves differ a lot depending on image complexity. Some ways out are mentioned. Some of them have been already tested (although not thoroughly enough), other directions of the future research seem to be perspective.

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Переваги та недоліки двоетапного підходу до забезпечення бажаних параметрів при стисненні зображень з втратами

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Анотація. **Об'єктом** дослідження є процес стиснення зображень з втратами. **Предметом** дослідження є двоетапний підхід до забезпечення бажаних параметрів (якості та ступеня стиснення) для різних кодерів. **Мета** дослідження полягає у тому, щоб переглянути переваги двоетапного підходу до стиснення з втратами, проаналізувати причини недоліків і запропонувати можливі шляхи усунення цих недоліків. **Використані методи:** лінійна апроксимація, чисельне моделювання, статистичний аналіз. **Отримані результати:** 1) основна перевага розглянутого підходу полягає в тому, що в більшості застосувань він забезпечує суттєве підвищення точності забезпечення бажаного значення контрольованого параметра стиснення після другого кроку порівняно з першим кроком; 2) підхід є досить універсальним і може бути застосований для різних кодерів і різних параметрів стиснення з втратами, які необхідно забезпечити; 3) основні проблеми та обмеження виникають через використання лінійної апроксимації та істотну різницю в поведінці кривих стиснення/спотворення для зображень різної складності; 4) існують способи уникнути недоліків підходу, які використовують адаптацію до складності зображення та/або використовують певні обмеження на другому кроці. **Висновки:** за результатами дослідження варто 1) розглянути більш складні апроксимації кривих стиснення/спотворення; 2) приділити більше уваги адекватним і швидким алгоритмам характеристики складності зображення перед стисненням; 3) використати показники якості, які мають квазілінійні криві стиснення/спотворення для даного кодера.

Ключові слова: стиснення зображень з втратами; контроль якості; ступінь стиснення; метрика якості; двоетапний підхід; переваги та недоліки.