This paper deals with lossy compression applied to grayscale noisy images using several coders. The case of additive white Gaussian noise is considered as the first step in studying the problem. A special attention is paid to quite new coders AVIF and HEIF for which, to the best of our knowledge, lossy compression of noisy images of different complexity has not been thoroughly considered yet. It is shown that optimal operation point is possible for all coders under certain conditions according to different quality metrics including conventional peak signal-to-noise ratio and visual quality metrics such as PSNR-HVS-M and MS-SSIM. The compression parameters (metrics) in optimal operation point significantly depend on image complexity and noise intensity where the existence of optimal operation point is more probable for simple structure images and/or intensive noise. Comparison of metric values in optimal operation point for the considered coders shows that slightly better characteristics are provided by better portable graphics (BPG) and advanced discrete cosine transform (ADCT) coders. The results for JPEG are significantly worse. The AVIF and HEIF encoders provide similar results and they outperform JPEG significantly. Optimal operation point for all studied coders is observed more rarely for visual quality metrics than for peak signal-to-noise ratio. General tendencies concerning dependence of optimal compression parameters on noise intensity are presented. It is shown that compression ratio in optimal operation point is often larger than 20 and can be as large as 60. The problem with AVIF and HEIF is that it is currently unclear how to choose quality factor for them to carry out lossy image compression in the neighborhood of the corresponding optimal operation point. Meanwhile, there is the tendency to optimal quality factor reduction if intensity of additive white Gaussian noise increases. The directions of further research are discussed.

Keywords: lossy image compression, noise, optimal operation point, performance comparison

Problem overview

A general number of images acquired nowadays by different sensors rapidly increases where images are obtained by customer devices [1], medical equipment [2], from satellite and drones [3, 4] and so on. Image mean size increases as well. This results in problems of image transfer, processing, and storage [5, 6]. Hence, image compression is an operation typical for many modern applications [5–7]. Lossless and lossy compression are two options having their own advantages and drawbacks. Lossless compression does not introduce distortions but the compression ratio (CR) for this class of methods is usually too small and cannot be varied [8]. This explains popularity of lossy compression represented by a wide variety of the corresponding techniques [7, 8]. Lossy compression produces distorted images but is often possible to control distortions and provide an appropriate trade-off between the attained CR and compressed image quality. Recall that quality can be characterized directly by some standard or

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In most applications of lossy compression, an image subject to compression is supposed noise-free or, at least, possible noise presence is ignored. Meanwhile, there are applications for which an acquired image is noisy [11–13]. Then, approaches to design and analysis of lossy compression of noisy images differ from those ones typical for lossy compression of noise-free images [14, 15]. This deals with specific noise filtering effect that takes place in lossy compression of noisy images as well as possible presence of optimal operation point (OOP) [14–16]. OOP is such a value of a parameter that controls compression (PCC) for a given coder for which compressed image is “the closest” to the corresponding true (noise-free) image according to a chosen quality metric and closer than the corresponding noisy (original, uncompressed) image. Here it is worth noting that OOP existence depends on image properties, noise type and intensity, a coder and a metric used. If OOP for a given noisy image and coder exists, then it is reasonable to compress it in OOP; otherwise, other recommendations on PCC setting can be taken into account [17].
Possible existence of OOP has been demonstrated for JPEG and JPEG2000 [18] in [15], for AGU [19], ADCT [20] and BPG [21] coders in [15], [16], and [17], respectively. Note that PCCs for these coders are different: quality factor (QF) for JPEG, bits per pixel (BPP) for JPEG2000, quantization step (QS) for the AGU and ADCT coder, parameter Q for the BPG encoder. This leads to the necessity to carry out special studies for designing the procedures of PCC setting in OOP (if it exists) for each coder depending on noise intensity. For AGU, ADCT, and BPG encoders, these procedures are quite simple under assumption that noise characteristics are a priori known or have been accurately estimated in advance [22, 23]. Meanwhile, for JPEG and JPEG2000, determination of QF and BPP in OOP requires iterative procedures with multiple compression and decompression.

Recently, new encoders, namely AVIF [24] and HEIF [25], have been designed and shown to be rather efficient. Meanwhile, to the best of our knowledge, the studies concerning application of these encoders to compression of noisy images have not been carried out. Thus, the paper goal is to check whether or not OOP is possible in lossy compression of noisy images by AVIF and HEIF. If yes, then we would like to compare the performance characteristics in OOP for these two encoders to data for other known encoders. As a starting point of such studies, we consider the case of grayscale images corrupted by white additive Gaussian noise (AWGN).

**Analysis of recent sources**

It is known that lossy image compression techniques are usually characterized by rate-distortion curves (RDCs), i.e. dependences of some parameter (metric) on PCC used for a given coder. Such dependences are usually monotonic functions. The examples are dependences of peak signal-to-noise ratio (PSNR) on QF for JPEG that are monotonously increasing functions [26] or dependences of PSNR on QS or CR for AGU [27] that are monotonously decreasing ones. This monotonicity shows the main tendency that quality of a compressed image becomes worse according to any metric if CR increases (BPP decreases). Then, it becomes easy to compare the coders’ performance by fixing CR for a given image and comparing the values of a considered metric. An example of RDCs (dependence of visual quality metric PSNR-HVS-M (https://ponomarenko.info/psnrhvs.htm) on CR for five different coders for a 512×512 pixel fragment of dental medical image is presented in Fig. 1. As one can see, the ADCT, BPG and modified AGU encoders provide significantly better quality of compressed image for a wide range of CR values according to the visual quality metric PSNR-HVS-M expressed in dB (larger values correspond to a better quality). Taking into account that visually noticeable distortions start to appear when PSNR-HVS-M is smaller than 40 dB, it is possible provide visually lossless compression for the ADCT, BPG and modified AGU encoders for CR up to 14 whilst the distortions become visible for JPEG and JPEG2000 is CR exceeds 10.

The situation is more complex in lossy compression of noisy images. Then, one might analyze not only traditional RDCs (as in Fig. 1) but also dependences for metrics calculated between compressed and noise-free images. In practice, it is impossible to obtain such dependences since noise-free image is absent, but it is possible to obtain them for simulated data when noise is artificially added to a noise-free image and then the obtained noisy image is compressed in a lossy manner [15–17].

![psnrhvs vs. compression ratio](image)

Fig. 1. RDCs for five encoders for a 512×512 pixel fragment of dental medical image

Fig. 2 presents such dependences for the conventional grayscale test image Peppers corrupted by AWGN with zero mean and variance $\sigma^2$ equal to 100 (all noise-free test images considered below are 8-bit). A problem was to present all dependences together since PCCs are different for different coders. Because of this, the horizontal axis is used for the following PCCs: QF for JPEG, AVIF, and HEIF where smaller values correspond to a larger CR; QS and the parameter Q for the ADCT and BPG encoders, respectively, where larger QS and Q relate to a larger CR. As one can see, the main observations are the following:

1) **PSNR** is about 28 dB (approximately equal to $10\log(2552/\sigma^2)$ for small CR (that corresponds to small QS and Q and larger QF);
2) PSNR is larger than 28 dB for certain interval of PCC values where maxima are observed for QS=41 for ADCT, Q=35 for BPG, QF=15 for JPEG, QF=25 for HEIF, and QF=31 for AVIF coders; this means that OOPs according to PSNRtc exist for all five encoders;

3) PSNRtc values in OOP are different; PSNRtc is the smallest for JPEG, and it is the largest for the BPG encoder;

4) PSNRtc values for the encoders HEIF and AVIF in OOP are almost the same; it is also worth noting that PSNRtc in neighbor QF values for these two coders are the same.

The dependences can be compared in another way – using CR as horizontal axis. The obtained data are represented in Fig. 3. As one can see, compression in OOP (with providing the largest possible PSNRtc) produces sufficiently different values of CR: about 20 for JPEG, about 24 for the ADCT coder, and larger than 40 for the HEIF, AVIF, and BPG encoders. Thus, although ADCT coder provides slightly larger PSNR_{OOP} (PSNR_{tc} in OOP), it produces significantly smaller CR_{OOP}(CR in OOP). Because of this, the modern encoders BPG, AVIF and HEIF can be preferable.

It might also happen that OOP is absent. Fig. 4 shows an example of the corresponding dependences for the test image Baboon (known to be highly textural or having complex structure) corrupted by AWGN with σ²=100. Formally, there is no OOP for all encoders (although there are local maxima for the ADCT and BPG encoders in which PSNR_{tc} are slightly smaller than PSNR_{tc}(CR→1). JPEG produces the smallest PSNR_{tc} in all the considered range of CR. The BPG and ADCT encoders provide better PSNR_{tc} than AVIF and HEIF encoders for CR≈6. However, starting from CR≈20, there is practically no difference for the BPG, ADCT, AVIF, and HEIF encoders.

Having explained the phenomenon of OOP and its possible existence or absence, we would like to recall the basic tendencies known from the earlier obtained results. First, OOP can exist not only according to traditional metric such as PSNR but also according to visual quality metrics [17] such as aforementioned PSNR-HVS-M or MS-SSIM [28]. Second, if the noise variance increases, PCC corresponding to OOP shifts towards its value that corresponds to a larger CR (i.e., a larger Q or QS and smaller QF). Third, if noise variance increases, probability that OOP exists increases as well [16, 29]. Fourth, PCC_{OOP} for conventional and visual quality metrics are almost the same. These properties will be checked in the next section of this paper.

Presentation of the main material

Let us start our analysis from considering the data for the visual quality metric MS-SSIM for which it is known that its maximal possible value is equal to unity and a larger MS-SSIM relates to better visual quality. Dependences of MS-SSIM_{tc} on CR are given in Fig. 5 for the test image Peppers. The first observation is that OOP exists for all five considered coders where the largest MS-SSIM_{tc} is again observed for the BPG encoder and the worst...
takes place for JPEG. Compression in OOP (according to MS-SSIMtc) produces CR about 23 for JPEG, about 25 for the ADCT coder, and larger than 40 for the HEIF, AVIF, and BPG encoders. This example confirms that OOPs according to different metrics are almost the same.

Consider now the plots for the test image Baboon corrupted by AWGN with $\sigma^2=196$ (Fig. 6). The main observations are the following. First, for three coders (BPG, ADCT, HEIF), OOPs are present (although OOPs were absent for $\sigma^2=100$, see the plots in Fig. 4). The results are again the best for the BPG encoder and the worst for JPEG. Second, positions of maxima have shifted towards larger CR values.

Finally, let us also present the plots MS-SSIMtc vs CR for the test image Peppers corrupted by AWGN with variance equal to 100 (Fig. 5) and 196 (Fig. 9). As seen, OOPs take place for all five encoders where the best results are provided by the BPG encoder. The values of CR_{OOP} are practically the same as for the PSNR metric (Fig. 8) for the corresponding coders. Meanwhile, the values of CR_{OOP} are larger than for the same test image but the smaller noise variance (compare to data in Fig. 5).

Therefore, we can state that the properties earlier observed for JPEG, ADCT, and BPG encoders take place for AVIF and HEIF as well. The possibility of OOP existence for them according to different metrics is clearly demonstrated. The performance characteristics are significantly better than for JPEG and are quite similar to those ones observed for the BPG and ADCT encoders although, in aggregate, the results for the BPG encoder are slightly better.
Meanwhile, there are several questions valuable for practice that have left not answered. The main among them is how to determine the OOP (\(\text{QF}_{\text{OOP}}\)) for a given image and noise variance. Second, we wonder do the discovered properties hold for other than optical (e.g., medical or remote sensing) types of images. Third, a question is whether or not it is possible to predict OOP existence before compression.

**Conclusions**

We have considered the task of lossy compression of grayscale images corrupted by AWGN by five coders including such modern ones as AVIF and HEIF. It is shown that the effects earlier found for other coders such as JPEG, ADCT, and BPG (in particular, possible OOP existence) take place for AVIF and HEIF as well. The results for AVIF and HEIF are of about the same level as for ADCT, slightly worse than for the BPG encoder, but significantly better than for JPEG. The OOP possible existence is shown for two optical test images of different complexity according to both conventional and visual quality metrics (especially, for the cases of intensive noise). It is stated that the studies have to be continued for other types of the images and noise. The main practical issue is to design a procedure to determine and set \(\text{QF}_{\text{OOP}}\).

**References**


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