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Efficient SEM Image Compression for High-Quality Reproduction of Nanomaterial Images using Lapped Biorthogonal Transform and Block Variance Classified Variable Rate Quantization

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Abstract— *Nanomaterial imaging is an integrated and essential part of the nanotechnology. It plays a vital role in the effective development, analysis and characterization of the nanomaterials. Currently, nanoimaging technology involves utilization of techniques like Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) etc. To reduce the computational complexity, storage space, and the transmission bandwidth, the SEM or TEM nanomaterial images must undergo to the high compression through the compression standard developed by Joint Photo Graphics Expert Group (JPEG). The higher compression of SEM images significantly reduces the quality and hence highly affects the development and analysis results of the nanomaterials. This paper presents a new SEM image coder to achieve high-quality compression of nanomaterial SEM images using Lapped Biorthogonal Transform (LBT) and a new quantization technique which provide variable rate quantization based on the classification of blocks variance. The obtained result shows significant improvement in the quality of the reconstructed SEM images in terms of Peak Signal to Noise Ratio (PSNR) and Mean Square Error (MSE) compared to the available JPEG compression standard.*

Keywords— *Nanomaterial Imagining, Scanning Electron Microscopy (SEM), Nanomaterial Image Compression, JPEG compression technique, LBT, Variable rate Quantization.*

1. INTRODUCTION

In the past few decades, a rapid growth in nanotechnology and nanomaterials have been progressively observed. The nanotechnology involves imaging, measuring, modeling, and manipulating of matter at nanoscale. The Scanning Image Microscopy (SEM) imaging is one of the prominent tool commonly utilized for the nanomaterials imagining [1-2]. Moreover, the fast development and characterization of advanced nanomaterials involve precise imaging over higher bit depth with large dimension to store minute information of materials for proper analysis. The higher bit depth and high dimension imaging requires very high storage space and limits the analysis with the higher time complexity. This level of imagining also requires higher bandwidth for the transmission of the images over the channel. All these critical issues incur the requirement of the image compression techniques which can reduce the dimension of the SEM images with good quality reconstruction ability. Currently, the JPEG compression standard is the choice for the compression of the SEM images. Although, the JPEG standard has the ability to offer good quality compression over higher bitrates, but the current imaging scenario demands higher compression, that is, compression at very low and low bitrates. Over these bitrates, the compression performance of the JPEG standard often suffers from the serve blocking artifacts and hence delivers poor compression performance. Therefore this paper presents an advanced SEM image coder to achieve higher quality compression and effectively alleviates the bottleneck problems related to the nanomaterials imaging. The proposed SEM image coder utilizes lapped biorthog-onal transform (LBT) to reduce the blocking artifacts over low bitrate compression because the LBT transform has smoother stop band characteristics as compared to the Discrete Cosine Transform (DCT) used in the JPEG coder. Further, a new variable bit rate quantization technique is also proposed to enhance the reconstruction capability of proposed coder. The proposed variable bitrate quantizer works on the classification of elemental image blocks based on variance parameter and applies variable quantization to different classes for preserving the important image information during quantization process.

The remaining paper is organized as follows. The description of the available JPEG standard and the proposed SEM image coder are presented in section 2 and section 3 respectively. The resultant compression perform-ance is presented in section 4, which is followed by the conclusion of the present work in section 5.

2. JPEG IMAGE COMPRESSION STANDARD

JPEG is one of the important lossy image compression technique, which is currently serving for the compression

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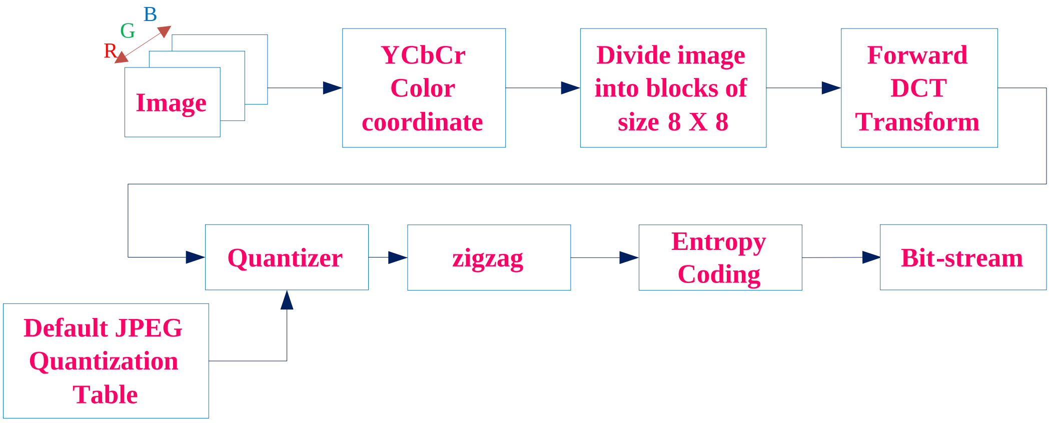


Fig. 1: The baseline JPEG Encoder

of nanomaterial images. The JPEG standard consists of a sequence of steps in the mapping of the input image to the compressed bit stream [3-6]. The basic steps of the JPEG standard is shown in Fig. 1, in which the first step after color coordinate conversion is to divide the three color components of the image into non-overlapping blocks of size 8×8. Each individual image block is then transformed by DCT transform to decorrelate the image block pixels.

2.1 Discrete Cosine Transform (DCT)

The mathematical definition of the Forward DCT and the Inverse DCT are as follows [7]:

$$F(u,v)=\frac{2}{N}C(u)C(v)\sum_{x=0}^{N-1}\sum_{y=0}^{N-1}f(x,y)\cos\left[\frac{\pi(2x+1)u}{2N}\right]\cos\left[\frac{\pi(2y+1)v}{2N}\right] \quad (1)$$

for $u=0,...,N-1$ and $v=0,...,N-1$

where $N=8$ and $C(k)=\begin{cases}1/\sqrt{2} & \text{for } k=0\\ 1 & \text{otherwise}\end{cases}$

$$f(x,y)=\frac{2}{N}\sum_{u=0}^{N-1}\sum_{v=0}^{N-1}C(u)C(v)F(u,v)\cos\left[\frac{\pi(2x+1)u}{2N}\right]\cos\left[\frac{\pi(2y+1)v}{2N}\right] \quad (2)$$

for $x=0,...,N-1$ and $y=0,...,N-1$ where $N=8$.

The *f(x,y)* is the intensity value of each pixel in the selected 8×8 image block, and the *F(u,v)* is the DCT coefficient after transformation. In the literature, the DCT is considered as the practically optimum transform which provides optimal pixel decorrelation close to KLT prior to the JPEG quantization. However, at the low bitrate compression, it leaves the block boundaries which is also known as blocking artifacts.

2.2 JPEG Quantization

After DCT transformation the transform coefficients are then quantized using a variable rate uniform scalar quantizer. During this process, every coefficient in the 8×8 DCT matrix is divided by a corresponding quantization value. The JPEG quantized coefficient is given by 3, and the reverse process can be achieved by 4.

$$F(u,v)_{Quantization}=round\left(\frac{F(u,v)}{Q(u,v)}\right) \quad (3)$$

$$F(u,v)_{deQ}=F(u,v)_{Quantization}\times Q(u,v) \quad (4)$$

The JPEG standard does not specify any quantization table for quantization process, though a possible table is suggested as examples in Annex K as shown in Fig. 2, which is used to quantize the DCT blocks of gray scale images.

The default JPEG quantization table delivers a constant bitrate compression for a particular gray scale image. However, the scaled version of this default table (obtained by multiplication by a variable suppose "q") is used to achieve variable rate compression.

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

Fig. 2: Default JPEG quantization table, given in Annex K.

2.3 JPEG Entropy Coding

JPEG Entropy coding is basically the process of further compression of quantized DCT coefficients using lossless compression techniques. In JPEG standard Huffman coding technique has been used to map the quantized transform coefficients into compressed bit stream [3].

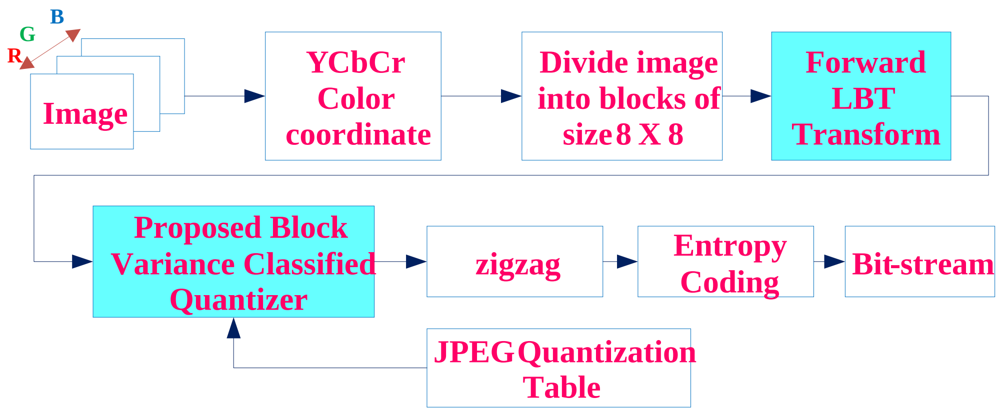


Fig. 3: Proposed SEM Image Encoder

3. PROPOSED SEM IMAGE CODER

This section briefly presents the design process and the structure of the proposed SEM image coder. As the ultimate aim is to design an image coder which can deliver higher decompression quality as compare to the available JPEG coder, this work proposes serious modifications on this available standard.

The first modification proposed is to replace the DCT transform with the Lapped Biorthogonal Transform (LBT). The second modification is proposed for the quantization process in which a new variable bit rate quantization strategy is proposed to efficiently preserve the important image information during quantization loss. The reaming blocks in proposed coder are same as JPEG standard. The block diagram of the proposed SEM image encoder is shown in fig. 3 and the detail description of the proposed blocks are given in the following subsections.

3.1 Lapped Biorthogonal Transform (LBT)

The LBT is a non-orthogonal version of Lapped Orthogonal Transform (LOT) [8-9]. For a one-dimensional signal, the LOT is constructed by designing a unitary transform which is characterized by a single overlapping rectangular matrix. The same manner LBT is characterized by the two separate transform matrices namely forward analyses matrix T_f and a backward synthesis matrix T_b in the form of [10],

$$T_f = \begin{pmatrix} p_{f1} & & & & \\ & p_f & & & \\ & & \ddots & & \\ & & & p_f & \\ & & & & p_{f2} \end{pmatrix}, T_b = \begin{pmatrix} p_{b1} & & & & \\ & p_b & & & \\ & & \ddots & & \\ & & & p_b & \\ & & & & p_{b2} \end{pmatrix} \quad (5)$$

Where p_f, p_b are the block matrices which forms the basis function of the forward and inverse LBT, and p_1, p_2 are the start and end block matrices. The forward and synthesis block matrices p_f and p_b for the LBT are obtained based upon a DCT related transformation matrix of the form given as

$$P_f = 1/2 \begin{bmatrix} D_e - V_f D_0 & D_e - V_f D_0 \\ j(D_e - V_f D_0) & -j(D_e - V_f D_0) \end{bmatrix} \quad (6)$$

$$P_b = 1/2 \begin{bmatrix} D_e - V_b D_0 & D_e - V_b D_0 \\ j(D_e - V_b D_0) & -j(D_e - V_b D_0) \end{bmatrix} \quad (7)$$

Where V_f and V_b are the scaling matrices for the analyses and synthesis LBT transform matrices T_f and T_b respecti-vely. These two scaling matrices V_f and V_b are basically responsible for the conversion of LOT into LBT and are given as,

$$V_f = \begin{pmatrix} \sqrt{2} & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} and\, V_b = V_f^{-1} \begin{pmatrix} 1/\sqrt{2} & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} \quad (8)$$

If the input signal be a column vector x, with transform output y, the LBT forward and inverse transformation is then given by relationships,

$$y = T_f * x \quad (9)$$

$$\hat{x} = T_b\, y \quad (10)$$

Where * represents complex conjugate transposition.

3.2 Proposed Block Variance Classified Variable Rate Quantizer

As discussed earlier, in JPEG standard, a scaled version of default 8×8 quantization matrix has been used to

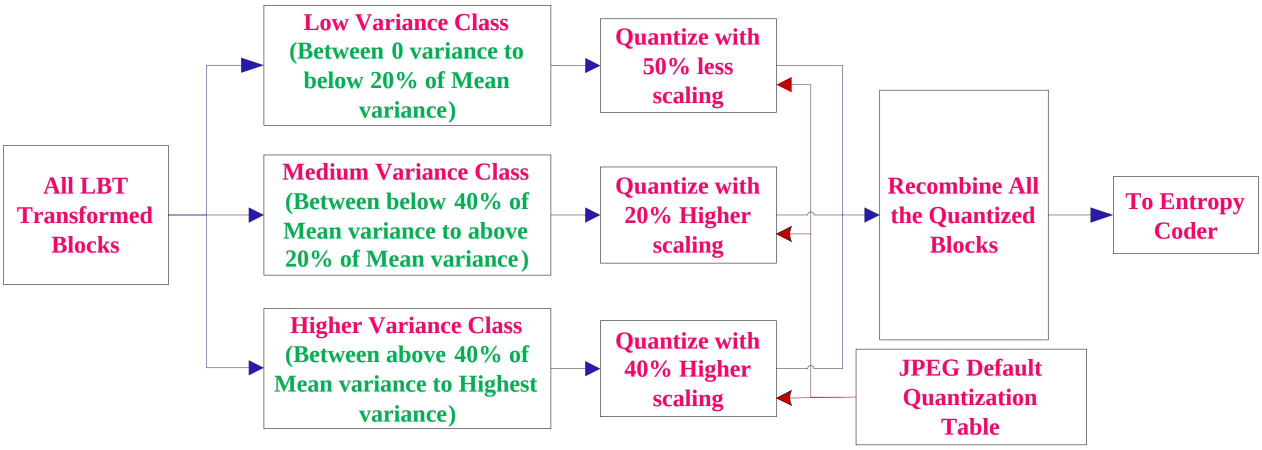


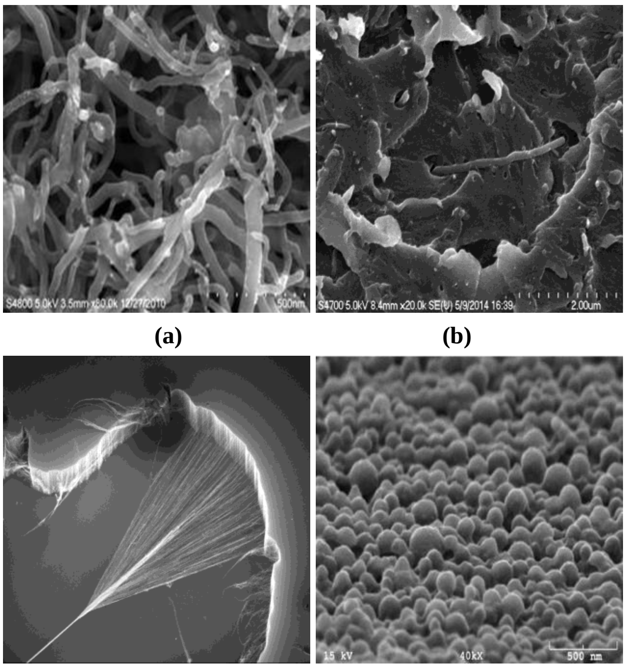
Fig. 4: Proposed block classified variable rate quantizer

quantize the DCT coefficients to achieve variable bitrate compress-ion for the grayscale images. The default JPEG quantization table for the luminescent component Y as specified in Annex K is shown in Fig. 2. Since the pixel statistics of the natural images for all the individual 8×8 image blocks will not be always same. Hence quantizing all the image blocks with the same quantization table may not provide the optimal compression quality. Therefore, this paper proposes a new variable rate quantization technique to provide an optimal strategy to enhance the compression quality. In the proposed quantization technique all the 8×8 image blocks are classified in the three categories based the variance of the individual blocks. The different classes of blocks are then quantized with differently scaled JPEG quantization table. The basic idea used here is to lose less information from low variance blocks while applying coarse quantizat-ion to the medium and higher variance blocks. The block diagram representation of the proposed variable rate quantizer is shown in Fig. 4.

4. RESULTS AND DISCUSSIONS

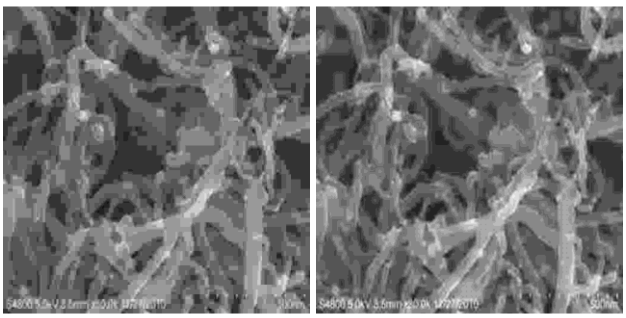
In this section, we will present the results obtained after compression and decompression of the Nanomaterial SEM images for different bitrates using proposed coder and default JPEG compression standard. To evaluate the compression performance of both the image coder's four different nanomaterial SEM images each of size 512×512 as shown in Fig. 5 have been used. The compression performance has been assessed with the help of PSNR and MSE image quality indexes over various bitrates.

After the compression and decompression of first SEM test image at bitrate 0.17 using proposed coder and JPEG coder, the obtained reconstructed images are shown in Fig. 6.



(a) (b) (c) (d)

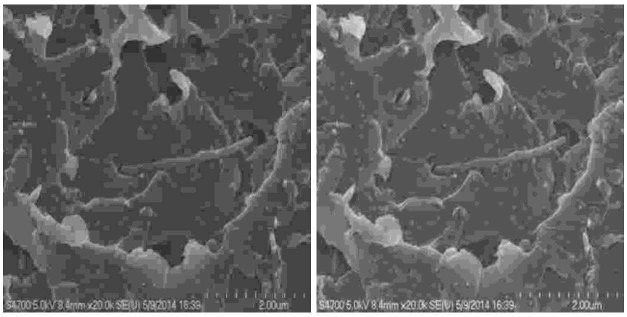
Fig. 5: Nanomaterial SEM test images. (a) Carbon Nanotubes, (b) Ultra-strong polymer-1, (c) Ultra-strong polymer-2, (d) PLGA Nano Particles.



(a) (b)

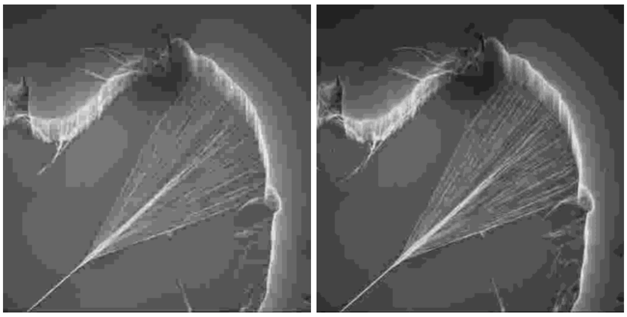
Fig. 6: Reconstructed images obtained for fist test image from, (a) JPEG coder, (b) Proposed SEM image coder.

From Fig. 6, we can see that at 0.17 bitrate the JPEG has PSNR of 15.53 dB, while the proposed coder has PSNR of 16.30 dB, thus there is a 0.77 dB gain in the reconstruction quality. The visual inspection of above figure also confirms the superior reconstruction quality of the proposed SEM image coder as it generates very less blocking artifacts compared to the available JPEG coder. Next, the similar analysis is performed for remaining test images and the reconstruction results at different bitrates 0.0823, 0.067 and 0.099 bpp, are respectively shown in Fig. 7 to Fig. 9.



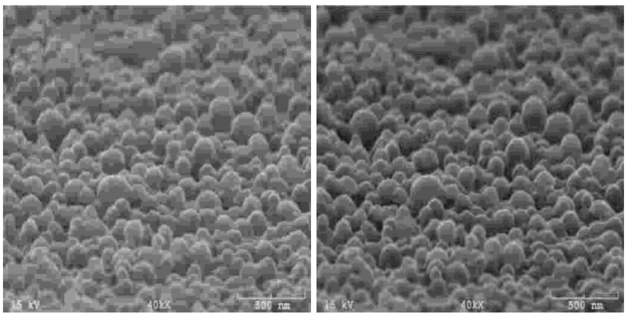
(a) **(b)**

Fig. 7: Reconstructed Images obtained for second test image from, (a) JPEG coder, (b) Proposed SEM image coder.



(a) **(b)**

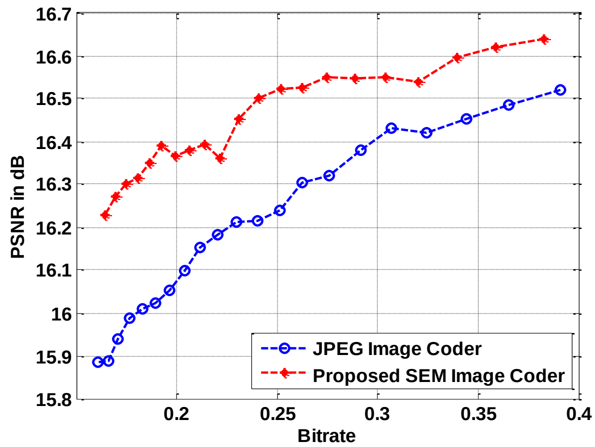
Fig. 8: Reconstructed Images obtained for third test image from, (a) JPEG coder, (b) Proposed SEM image coder.



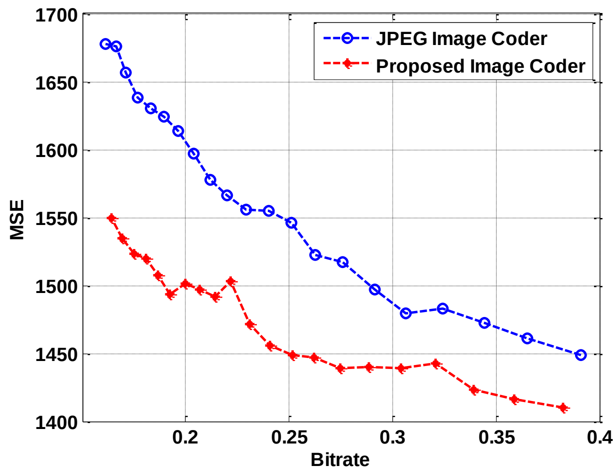
(a) **(b)**

Fig. 9: Reconstructed Images obtained for fourth test image from, (a) JPEG coder, (b) Proposed SEM image coder

From the reconstruction characteristics presented above for the other three test images, it is clearly reflected that the proposed SEM image coder outperforms the existing JPEG coder in terms of higher quality reconstruction. Further, for the complete compression performance evaluation, the image quality indexes PSNR and MSE obtained for first test image using both the coders over various bitrates have been plotted in Fig. 10.



(a)

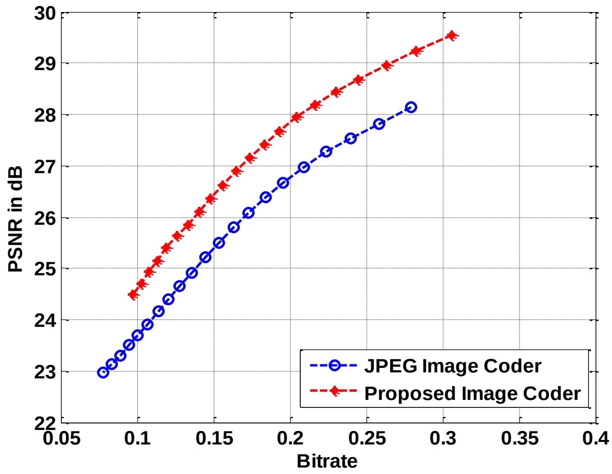


(b)

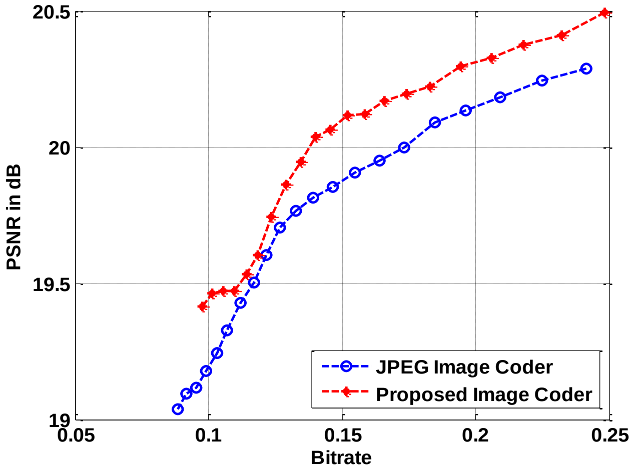
Fig. 10: Rate distortion curves obtained for the first test image, (a) PSNR curves and (b) MSE curves.

From Fig. 10, it is clearly evident that the proposed SEM image coder outperforms the available JPEG coder for all the bitrate levels as it delivers significantly higher PSNR and lower MSE values. Similarly, both the image coders are evaluated for remaining three test images and the PSNR curves obtained are shown in Fig. 11.

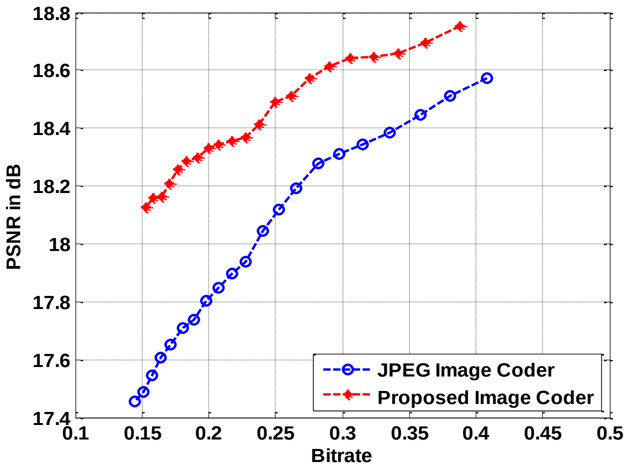
Again from the above PSNR curves, it is clearly reflected that the proposed SEM image coder offers better quality image compression for all the nanomaterial SEM test images as compared the existing JPEG standard.



(a)



(b)



(c)

Fig. 11: PSNR curves obtained for,
(a) second test image,
(b) third test image and (c) fourth test image.

5. CONCLUSIONS

In this paper, a new nanomaterial SEM image coder has been developed using Lapped Biorthogonal Transform (LBT) and a new variable rate quantization technique. The proposed image coder has been extensively evaluated with the help of four different nanomaterial SEM images over different bitrates. It is reported that the proposed coder delivers higher quality compression and provides 0.75dB to 1.2dB PSNR gain compared the existing JPEG compression standard.

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