Compression of 3D Medical Images for Wireless Transmission

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1. Introduction

Picture archiving and communication systems (PACS), which contain a collection of specialized networks and software, are commonly used for storage and distribution of 3D medical images. In recent years, the wide pervasiveness use of telemedicine technologies has motivated the integration of mobile devices, such as Personal Digital Assistants, into PACS in order to allow immediate diagnosis by a doctor at any time and place [1]. Consequently, telemedicine applications require that 3D medical images be efficiently transmitted over error-prone wireless networks of various bandwidth capacities.

In this letter, we introduce a compression method with optimal channel protection for transmission of 3D medical images over error-prone wireless networks. Our method, which is based on the 3D integer wavelet transform (3D-IWT) and the embedded block coding with optimized truncation (EBCOT) algorithm, allows compression of 3D medical imaging data into a layered bit-stream that is scalable in quality and resolution, up to lossless reconstruction. The method features optimal channel protection, which is achieved by employing an optimization technique that assigns protection bits to the different sections of the compressed bit-stream based on their mean energy content. The method realizes channel protection by concatenating a cyclic redundancy check (CRC) outer coder and an inner rate-compatible punctured convolutional (RCPC) coder.

We evaluated the robustness of the proposed method over a Rayleigh-fading channel, which effectively models the effect of a propagation environment on radio signals used by wireless devices. Performance comparisons on real magnetic resonance imaging (MRI) volumes are made with the cases of equal channel protection (ECP) and unequal channel protection (UCP). Our results show that the proposed method outperforms the ECP and UCP techniques over a variety of channel conditions and transmission bit-rates.

2. The proposed compression method

The proposed compression method with optimal channel protection is depicted in Fig. 1. At the encoder side, we first apply a 3D-IWT with dyadic decomposition and R levels of decomposition to an input 3D medical image. This type of wavelet transform guarantees perfect invertibility and thus allows for perfect reconstruction of the signal [4]. After the 3D-IWT, we group the wavelet coefficients into code-cubes of $a \times a \times a$ samples. We employ a pyramid approach to define the size and position of code-cubes across the different decomposition levels, so that a code-cube of $a \times a \times a$ samples at position $\{x,y,z\}$ in a particular sub-band at decomposition level r depicts the same spatial information as the code-cube of $a/2 \times a/2 \times a/2$ samples at position $\{x/2,y/2,z/2\}$ in the equivalent sub-band at decomposition level $r + 1$, where $r = 1$ is the first decomposition level (see Fig. 2). We encode each code-cube independently using a modified EBCOT with 3D contexts to create a separate scalable layered bit-stream for each code-cube [5,6]. We then generate the compressed bit-stream representing the 3D image by collecting the incremental contributions from the various code-cubes into a number of quality layers, so that the code-cube contributions result in an optimal rate-distortion representation of the 3D image, for each quality layer L [5,6]. We use the information about the mean energy of the wavelet coefficients comprising each code-cube in an optimization process to optimally channel-protect the coded code-cubes, so that more protection bits are assigned to those coded code-cubes containing the most energy.

At the decoder side, after transmission over an error-prone wireless network, we first decode the channel-protected data and employ an error concealment technique to minimize the effect of channel errors. We then obtain the wavelet coefficients by applying the EBCOT decoder. Finally, we obtain the re-constructed 3D image by applying an inverse 3D-IWT.

3. Optimal channel protection assignment

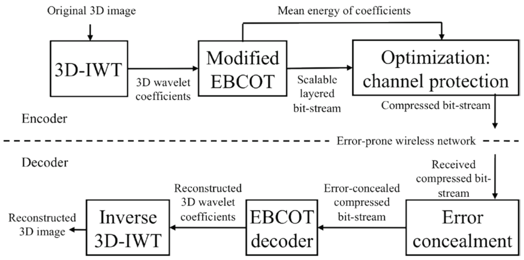

Fig. 1. Proposed compression method. 3D-IWT: three-dimensional integer wavelet transform. EBCOT: embedded block coding with optimized truncation.

We assign channel protection to the compressed bit-stream representing the 3D image based on the effect of bit-errors in each code-cube bit-stream to the overall mean-square error (MSE) of the reconstructed 3D image. Due to the entropy coding process of EBCOT, the distortion in the reconstructed 3D image depends on both the number and position of the bit-errors. A bit-error in the initial few bits of a code-cube bit-stream generally results in higher distortion compared to a bit-error in the later bits, since the initial few bits comprise the most significant bit-planes.

Code-cubes are encoded independently from each other and thus, bit-errors in one code-cube bit-stream do not propagate to others. In order to further limit error-propagation within a single code-cube bit-stream, we employ an error concealment technique at the decoder side. In this error concealment technique, after the occurrence of the first bit-error in a bit-plane, we assign a value of zero to the current and subsequent bit-planes, so that the MSE of a code-cube does not increase any further. Under this scenario, the maximum MSE (MMSE) of a code-cube i at quality layer L [hereafter referred to as code-cube (i, L)] is equal to its mean energy (i.e., errors in all the bit-planes of a code-block):

$$\mathrm{M}_{i,L} = \frac{1}{K}\sum_{k=1}^{K}\left(c_k - \hat{c}_k\right)^2 \tag{1}$$

where c_k is the kth sample of code-cube (i, L), $\hat{c}_k$ is the quantized representation of the kth sample of code-cube (i, L) associated with the bit-stream contribution to quality layer L, and K is the total number of samples in code-cube (i, L). The MMSE of code-cube (i, L) in sub-band s on a per-voxel basis over the entire 3D image may then be calculated as:

$$\overline{\mathrm{M}}_{i,L} = \frac{g_s}{N_s}\frac{q_s}{Q}\mathrm{M}_{i,L} = 2^{2r}\frac{g_s}{N_s}\mathrm{M}_{i,L} \tag{2}$$

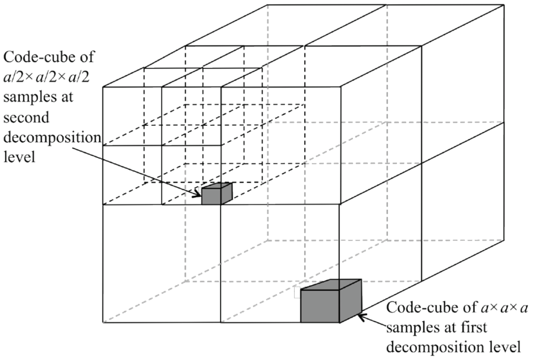

Fig. 2. A code-cube of a×a×a samples at the first decomposition level and the equivalent code-cube of a/2×a/2×a/2 samples at the second decomposition.

where Q is the total number of image voxels, r is the decomposition level to which code-cube (i, L) belongs (r = 1 denotes the first decomposition level), $q_s = Q/2^{2r}$ is the number of wavelet coefficients in s, N_s is the number of code-cubes in s (the code-cubes are of equal size), $\mathrm{M}_{i,L}$ is as defined in (1), and g_s is a factor used to compensate for the non-energy preserving characteristics of the bi-orthogonal Le Gall 5/3 wavelet filter [7].

The overall distortion of the 3D image at quality layer L can be then expressed as the summation of the individual distortions associated to each code-cube (i, L) multiplied by the probability of channel error P_e. The probability of channel error P_e is estimated from the current channel conditions and the RCPC coding rate chosen over a Rayleigh-fading channel [8,9]. For a 3D image coded using a total of I code-cubes, the overall distortion at quality layer L is then:

$$D^L = \sum_{i=1}^{I}\overline{\mathrm{M}}_{i,L}\cdot \mathrm{P}_e \tag{3}$$

where $\overline{\mathrm{M}}_{\mathrm{i},L}$ is as given in (2).

For a fixed target transmission rate, some of the code-cube bit-streams may have to be discarded in order to accommodate for the protection bits. Hence, the distortion in (3) can be expressed as follows:

$$D^L = \sum_{i=i}^{I}\overline{\mathrm{M}}_{i,L}\cdot \mathrm{P}_e\cdot \delta(i) + \sum_{i=i}^{I}\mathrm{m}_{i,L}\cdot\left[1-\delta(i)\right] \tag{4}$$

where $\mathrm{m}_{i,L}$ is the amount of MSE that will be added to the overall distortion if the bit-stream of code-cube (i, L) is discarded, and $\delta(i)$ is 1 if the bit-stream of code-cube (i, L) is included, otherwise it is zero.

We find the optimal channel protection at quality layer L by minimizing D^L in (4) under the following bit-rate constraint:

$$\sum_{i=1}^{I} \frac{S_{i,L}}{R_{i,L}} \cdot \delta(i) \leq R_{T,L} \quad (5)$$

where $R_{i,L}$ is the channel code rate for the bit-stream of code-cube (i, L), $S_{i,L}$ is the number of bits in the bit-stream of code-cube (i, L), and $R_{T,L}$ is the available transmission bit-rate at quality layer L.

We solve the optimization problem in Eqs. (4)-(5) by finding the points that lie on the lower convex hull of the rate-distortion plane corresponding to the possible sets of bit-stream assignments.

4. Performance evaluation

We tested the performance of our proposed method over a simulated Rayleigh-fading channel, which effectively models the fading effect on radio signals used by wireless devices in built-up urban areas where buildings and other objects attenuate, reflect, refract and diffract the signals [10]. We employed Jakes' model to simulate a Rayleigh-fading channel, where the channel conditions are specified by the average received signal-to-noise ratio ($\overline{\mathrm{SNR}}$) over the channel [10]. A low $\overline{\mathrm{SNR}}$ value corresponds to poor channel conditions, whereas a high $\overline{\mathrm{SNR}}$ value corresponds to good channel conditions. We used an MRI volume as the test image. The MRI volume comprises 50 slices of a human spinal cord [saggital view, 512×512 pixels per slice (pps), 8 bits per voxel (bpv)]. In order to obtain different channel protection rates, we punctured with a period of eight, the convolutional mother code of rate 1/4 and generator matrix g = [23 35 27 33] (in octal notation) [8]. The decoding process was performed using the Viterbi algorithm [9].

We decomposed the test images with four levels of decomposition in all three dimensions. We employed *32×32×32* samples per code-cube to create a scalable layered bit-stream with 20 quality layers, whose reconstruction quality progressively improves up to lossless reconstruction. We divided the code-cubes bit-streams to be channel-protected into smaller bit-streams of 384 bits. Each of these smaller bit-streams was first protected by an outer 16-bit CRC code defined by the polynomial 210 421 (in octal notation), followed by an inner RCPC code. The information regarding the channel code rates and number of protected code-cube bit-streams is assumed to be common knowledge to both the encoder and decoder and thus, no side information needs to be transmitted. We evaluated the robustness of the proposed method over two different channel conditions ($\overline{\mathrm{SNR}}$ =10dB and $\overline{\mathrm{SNR}}$ =25dB) with frequency-shift keying transmission, a data rate of 15 Kbit/s, a mobile speed of 5 Km/h, and a carrier frequency of 900 MHz, which is one of the operating frequencies for GSM mobile devices [11]. For comparison purposes, we also evaluated an ECP and UCP technique designed for the current channel conditions [12]. Similarly to the proposed method, these techniques employ a 16-bit CRC code (210 421 - in octal notation), followed by an inner RCPC code. The ECP technique assigns protection bits equally across all sections of the compressed bit-stream. The UCP technique assigns protection bits to the different sections according to their mean energy, but unlike the proposed method, it employs no optimization. Both techniques, ECP and UCP, discard code-cube bit-streams to accommodate for the protection bits in a similar manner to the proposed method. In all cases, the decoder performs error concealment on the received data, as explained in section 2

We tested each channel condition with 500 independent trials. Figure 3 shows the average PSNR (in dB) of the received 3D images after transmission at a variety of bit-rates. It can be seen that the proposed method achieves the highest average PSNR values over all channel conditions and transmission rates. This is a consequence of the optimization process employed to assign channel protection, in which the code-cube bit-streams containing the most energy of the image are assigned more protection at the expense of reducing the protection assigned to those code-cube bit-streams with low energy content.

5. Conclusions

We presented a 3D medical image coding method with optimal channel protection for transmission over error-prone wireless networks. The method is based on a 3D integer wavelet transform and the EBCOT algorithm and generates a scalable layered bit-stream. The method optimally assigns channel protection to the different sections of the compressed bit-stream according to their mean energy content. The channel protection is realized by concatenating an outer CRC code and an inner

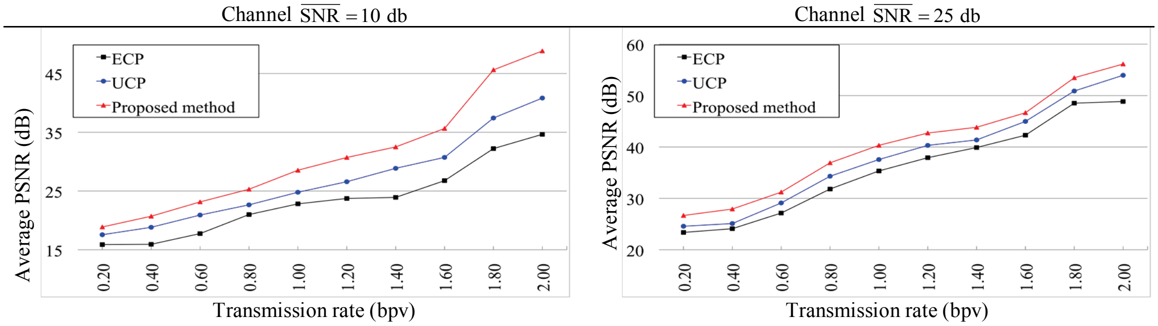

Fig. 3. Average PSNR values (in dB) of the reconstructed MRI slices (saggital view) of a human spinal cord after transmission over a Rayleigh-fading channel with different channel conditions.

RCPC code. We verified the robustness of the proposed coding method over a Rayleigh-fading channel with different channel conditions. Simulation results show that the proposed method outperforms the ECP and UCP techniques over a variety of channel conditions and transmission bit-rates.

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