3D MEDICAL IMAGE CODING WITH OPTIMAL CHANNEL PROTECTION FOR WIRELESS TRANSMISSION

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ABSTRACT

We propose a 3D medical image coding method with optimal channel protection for wireless transmission. The proposed method employs the 3D integer wavelet transform and a modified EBCOT with 3D contexts to create a scalable layered bit-stream. Optimal channel protection is attained by assigning protection bits to the different sections of the compressed bit-stream according to their mean energy content. The robustness of the proposed method is e-valuated over a Rayleigh-fading channel with a concatenation of a cyclic redundancy check code and a rate-compatible convolutional code. Comparisons are made with the cases of equal channel pro-tection and unequal channel protection. Simulation results show a significant improvement in reconstruction quality of the received 3D images.

Index Terms— Channel protection, EBCOT, medical images, lossless coding, wireless transmission, wavelet transform.

1. INTRODUCTION

Recent years have seen the amount of three-dimensional (3D) medical imaging acquisitions increase considerably, making the access and transmission of these data ever more complex. In current practice, 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. Furthermore, recent technological advances in telemedicine have accelerated 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.

Most of the work on 3D medical imaging access using mobile devices has focused on enabling the visualization of such data at the mobile devices, and little work has been done on designing co-ding and channel protection methods to access and transmit such data over error-prone wireless networks [1-3]. Grounded in this motivation, we propose a coding method with optimal channel pro-tection for transmission of 3D medical images over error-prone wireless networks. The proposed method employs a 3D integer wavelet transform (3D-IWT) and a modified version with 3D contexts of the embedded block coding with optimized truncation (EBCOT) algorithm to compress the 3D medical imaging data into a layered bit-stream that is scalable in quality and resolution, up to lossless re-construction. Optimal channel protection is attained by employing an optimization technique that assigns protection bits to the different sections of the compressed bit-stream based on their mean energy content. Channel protection is realized by concatenating a cyclic redundancy check (CRC) outer coder and an inner rate-compatible punctured convolutional (RCPC) coder. The robustness of the proposed method is evaluated over a Rayleigh-fading channel, which effectively models the effect of a propagation environment on radio signals, such as those used by wireless devices. Performance comparisons on real magnetic resonance imaging (MRI) and computed tomography (CT) 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. PROPOSED CODING METHOD

The proposed coding method with optimal channel protection is depicted in Fig. 1. At the encoder side, we first apply a 3D-IWT with dyadic decomposition to an input 3D medical image. This transform maps integers to integers and allows for perfect inverti-bility with finite precision arithmetic, which is required for perfect reconstruction of a signal [4]. We then group the wavelet coeffi-cients into 3D groups, which we call code-cubes. We encode each code-cube independently using a modified EBCOT with 3D con-texts to create a separate scalable layered bit-stream for each code-cube [5,6]. The information about the mean energy of the wavelet coefficients comprising each code-cube is then used in an optimi-zation 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 mini-mize the effect of channel errors. We then obtain the wavelet coef-ficients by applying the EBCOT decoder. Finally, we obtain the re-constructed 3D image by applying an inverse 3D-IWT.

There are two key techniques in the proposed compression method. The first is the independent coding of code-cubes. The second is the optimal channel protection of the compressed bit-stream. We will discuss them in the next sections.

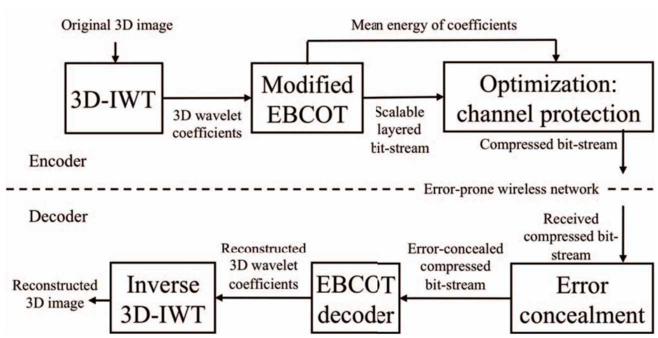

Fig. 1. Proposed coding method. 3D-IWT: three-dimensional integer wave-let transform. EBCOT: embedded block coding with optimized truncation.

2.1. Coding of code-cubes

In this work, we employ the bi-orthogonal Le Gall 5/3 wavelet filter implemented using the lifting step scheme to decompose a 3D input image into R levels of decomposition [4]. Each level of decomposition, r, produces eight 3D frequency sub-bands denoted as LLLr, LLHr, LHLr LHHr, HLLr, HLHr, HHLr, and HHHr. The approximation low-pass sub-band, LLL, is a coarser version of the original 3D image, while the other high-pass sub-bands represent the details of the image. The decomposition is iterated on the approximation low-pass sub-band. After wavelet decomposition, we group the wavelet coefficients into code-cubes of $a \times a \times a$ samples. We employ a pyramid approach to define the size of code-cubes across the different decomposition levels. In this approach, a code-cube of $a \times a \times a$ samples at position $\{x,y,z\}$ in decomposition level r is related to a code-cube of $a/2 \times a/2 \times a/2$ samples at position $\{x/2,y/2,z/2\}$ in decomposition level $r+1$, where $r=1$ is the first decomposition level. Fig. 2 shows the 3D-IWT sub-bands of a 3D image after two levels of decomposition in all three dimensions with a single code-cube in sub-bands HHH_2 and HHH_1.

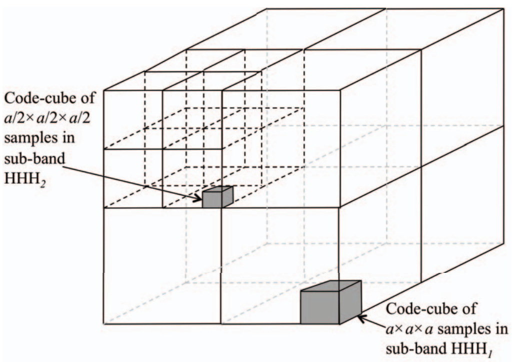

Fig. 2. 3D sub-bands of a 3D image after two levels of decomposition in all three dimensions with a single code-cube in sub-bands HHH_1 and HHH_2 [6]

We code each code-cube independently using a modified EBCOT with a 3D context model that exploits correlations in all three dimensions and improves coding efficiency, as previously proposed in our work in [6]. This particular 3D context model, which is based on a number of coding passes, employs the information about the magnitude and significance of the adjacent neighbors of a sample c in a given bit-plane p in order to best predict the magnitude and significance of sample c (see Fig. 3). Sample c is said to be significant in a given bit-plane p if and only if $|c| \geq 2^p$. The result is a separate bit-stream for each code-cube, which may be independently truncated in different lengths. We organize these independent truncated bit-streams into a number of quality layers to create a scalable layered bit-stream representing the entire 3D image. We do this by collecting the incremental contributions from the various code-cubes into the 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].

2.2. Optimal channel protection

In order to assign optimal channel protection to the compressed bit-stream representing the 3D image, we evaluate the effect of bit-errors (due to transmission errors) in each code-cube bit-stream to the overall mean-square error (MSE) of the reconstructed 3D image. Because the entropy coding process in the modified EBCOT is performed using binary arithmetic coding, the magnitude of the

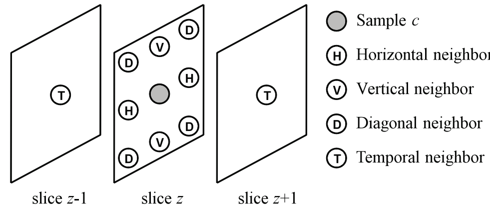

Fig. 3. The adjacent neighbors of sample c in the current (z), previous ($z-1$) and next ($z+1$) slice, used to predict the magnitude and significance of c [6]

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. Subsequent bit-errors gradually increase the value of the MSE of a code-block, until the maximum MSE value is reached, i.e., errors in all the bit-planes of a code-block.

Since code-cubes are encoded independently from each other, 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 a simple 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:

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

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 truncated bit-stream at 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:

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

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 an interleaved 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 $\overline{\mathrm{M}}_{i,L}$ 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. Due to the scalability properties of the compressed bit-stream, code-cube bit-streams should be discarded in a sequential order starting with those comprising the high-pass sub-bands and ending with those comprising the low-pass sub-band. 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:

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

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. When the bit-stream of code-cube (i, L) receives no channel protection, the channel code rate is equal to one.

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.

3. 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 and a CT volume as test images. The MRI volume comprises 50 slices of a human spinal cord [saggital view, 512×512 pixels per slice (pps), 8 bits per voxel (bpv)]. The CT volume comprises 120 slices (axial view, 512×512 pps, 12 bpv) of the Visible Male data set (National Library of Medicine - *www.nlm.nih.gov*). 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 coded code-cubes to be channel-protected into blocks of 384 bits. Each block 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. In order to erase the memory associated with a Rayleigh-fading channel, we employed a convolutional interleaver of depth 80 to interleave the protected data before transmission. 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-cubes 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 2.2

We tested each channel condition with 500 independent trials. Figure 4 shows the average PSNR (in dB) of the received 3D images after transmission at a variety of bit-rates. Note that the proposed method achieves the highest average PSNR values over all channel conditions and transmission rates, with an average improvement of 3 dB over the ECP technique and of 6.5 dB over the UCP technique. This is expected, since the proposed method optimally assigns protection bits to the compressed bit-stream to reduce the overall distortion of the 3D reconstructed image. Consequently, those code-cube bit-streams comprising the low-pass subbands and the most significant bit-planes are assigned more protection at the expense of reducing the protection assigned to those code-cube bit-streams comprising the high-pass sub-bands. Note that for good channel conditions ($\overline{\mathrm{SNR}}$=25dB), the performance of the three methods tends to be similar, as it is less probable to find bit-errors in the compressed bit-streams. Figure 5 illustrates a reconstructed slice of the test MRI volume transmitted at 0.60 bpv over a channel with $\overline{\mathrm{SNR}}$=10dB. Note the failure of the ECP technique to protect the most significant bit-planes of the image, which results in a poor reconstruction quality.

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 a modified version of EBCOT that exploits data correlations in all three dimensions 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 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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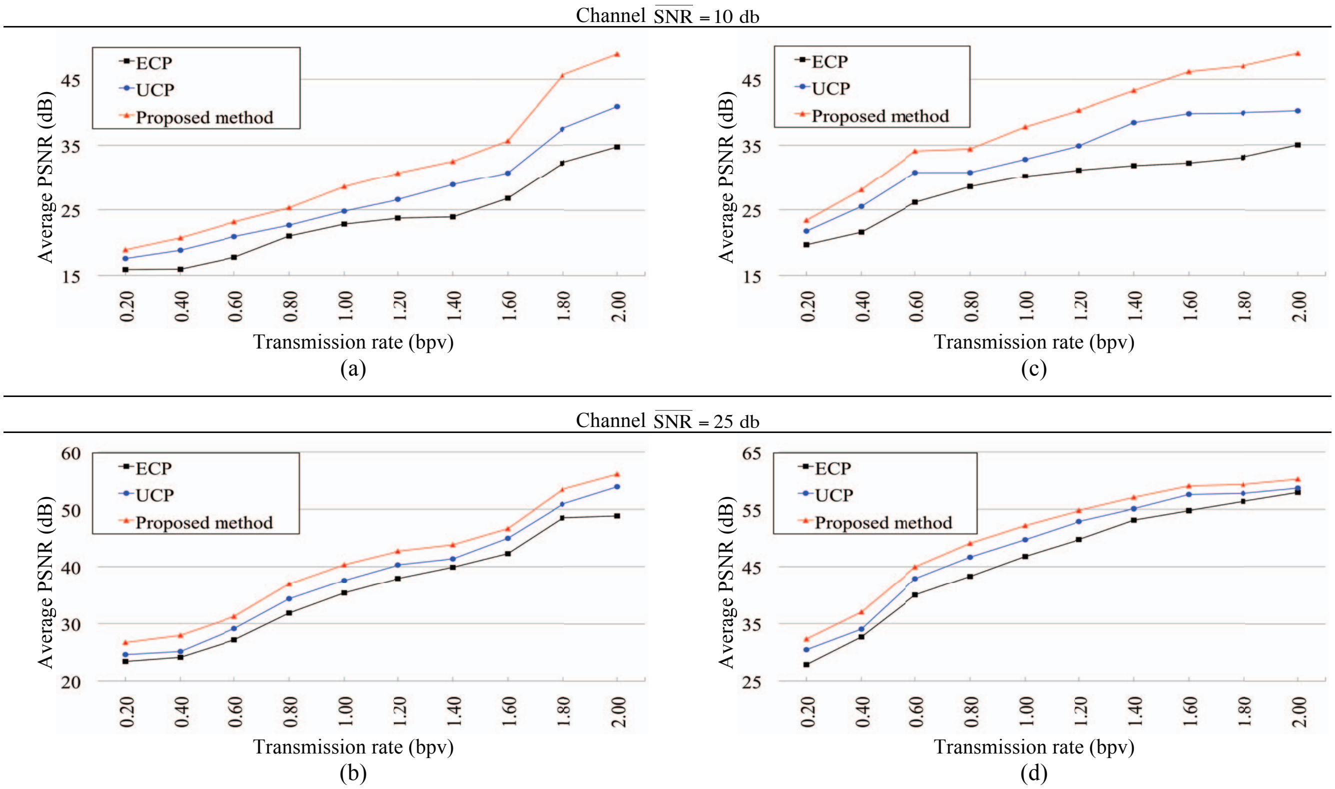
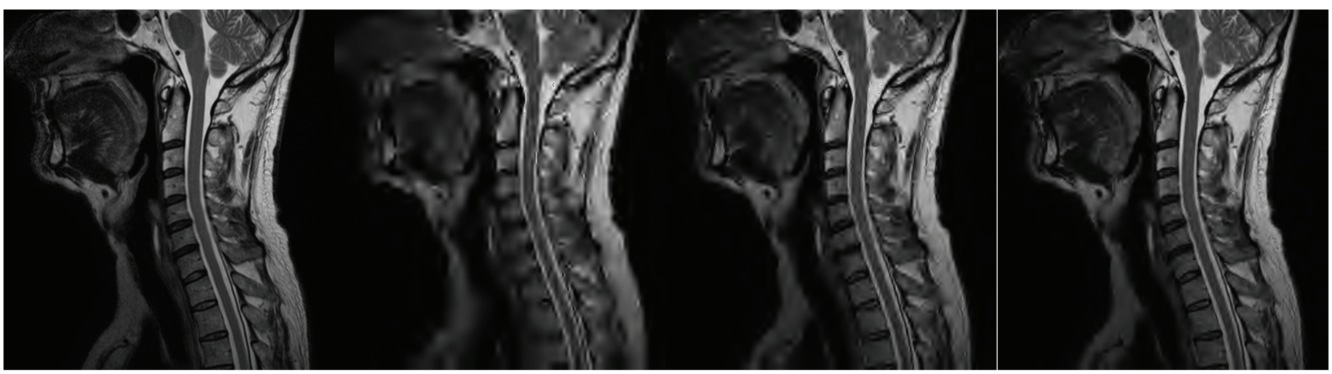


Fig. 4. Average PSNR values (in dB) of reconstructed medical imaging data after transmission over a Rayleigh-fading channel with different channel conditions. (a)-(b) MRI slices (saggital view) of a human spinal cord. (c)-(d) CT slices (axial view) of the Visible Male data set (*www.nlm.nih.gov*)



(a) Original image coded at 0.6 bpv (b) ECP technique: 17.75 dB PSNR (c) UCP technique: 20.91 dB PSNR (d) Proposed method: 23.15 dB PSNR

Fig. 5. Reconstructed slice of the test MRI volume transmitted at 0.6 bpv over a Rayleigh-fading channel ($\overline{\text{SNR}}$=10 dB). Images show the average quality.

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