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High efficient ECG compression based on reversible round-off non-recursive 1-D discrete periodized wavelet transform

Cheng-Tung Ku [a,d], King-Chu Hung [b,*], Huan-Sheng Wang [c], Yao-Shan Hung [e]

[a] Institute of Engineering Science and Technology, National Kaohsiung First University of Science and Technology, Taiwan
[b] Graduate Institute of Electronic Engineering and Computer Science, National Kaohsiung First University of Science and Technology, Taiwan
[c] Department of Computer and Communication Engineering, National Kaohsiung First University of Science and Technology, Taiwan
[d] Department of Information Management, Tzu Hui Institute of Technology, Taiwan
[e] Chung Shan Institute of Science and Technology, Taiwan

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Abstract

Error propagation and word-length-growth are two intrinsic effects influencing the performance of wavelet-based ECG data compression methods. To overcome these influences, a non-recursive 1-D discrete periodized wavelet transform (1-D NRDPWT) and a reversible round-off linear transformation (RROLT) theorem are developed. The 1-D NRDPWT can resist truncation error propagation in decomposition processes. By suppressing the word- length-growth effect, RROLT theorem enables the 1-D NRDPWT process to obtain reversible octave coefficients with minimum dynamic range (MDR). A non-linear quantization algorithm with high compression ratio (CR) is also developed. This algorithm supplies high and low octave coefficients with small and large decimal quantization scales, respectively. Evaluation is based on the percentage root-mean-square difference (PRD) performance measure, the maximum amplitude error (MAE), and visual inspection of the reconstructed signals. By using the MIT-BIH arrhythmia database, the experimental results show that this new approach can obtain a superior compression performance, particularly in high CR situations.

Keywords: ECG; Data compression; Wavelet transform; Reversible transformation

1. Introduction

Electrocardiogram (ECG) signal analysis is a non-invasive modality widely used for heart disease diagnosis and ambulatory monitoring [1]. Motivated by the demands of real-time data transmission and Holter recording, many ECG data compression methods under the crucial requirements of preserving clinical information have been proposed. Traditionally, these methods can be categorized into time- [2,3] and transform-domain [4–11] groups according to processed data. Transform-domain methods with correlation resistance generally have better compression performance than time-domain methods that are sensitive to the interference of high frequency components. However, considering the particularity of individual signal, it is appropriate to specify the third category able to involve some approaches that are designed for signal adaptation. In general, these approaches require a pre-process for the desire of codebook adaptation [12,13], error limitation [14], and alleviating artifact [15]. A brief review of the three-group categorization can be found in [16]. Recently, the wavelet-based approach [6–15] has attracted much attention from researchers due to simplicity and high compression performance.

Traditional wavelet-based ECG data compression methods applied the recursive pyramid algorithm [17] to perform the 1-D discrete wavelet transform (DWT). This DWT process is referred to as the 1-D RDWT where six stages of decomposition are usually required for each segment of ECG data. Thresholding and entropy coding are then incorporated to achieve data compression. Thresholding is used to reduce the dynamic range of all octave coefficients including scal-

* Corresponding author. Tel.: +886 7 6011000; fax: +886 7 6011113.
E-mail address: kchung@ccms.nkfust.edu.tw (K.-C. Hung).

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ing and wavelet coefficients. This dynamic range reduction process will produce truncation error and cause information loss in reconstructed data. Lossy compression methods try to optimize the compromise between CR and distortion. Fixed percentage zeros (FPZ) [6] and retrieved quality guaranteed (RQG) [5] are two best threshold-based schemes. In FPZ, thresholding is first used to keep fixed percentages of wavelet coefficients at zeros and followed by entropy coding. RQG is a filter bank-based compression method that improves FPZ with a target PRD as the criterion for threshold determination. Incorporating the thresholding into a hierarchical tree coding, the set partitioning in hierarchical trees (SPIHT) [7] is one best scheme with excellent compression performance and the capability of real-time process. This scheme uses the same threshold value, which is determined by the desired CR and should be 2^n (power of 2), for all octave coefficients.

To obtain high CR, reducing the dynamic range of high octave coefficients is usually required. However, the 1-D RDWT suffers from the word-length-growth effect. This word-length-growth effect is a crucial issue in wavelet-based data compression as well as in VLSI realization. The word-length-growth effect occurs when we desire to minimize the error propagation in inverse direction. Since the 1-D RDWT uses the same filters in forward and inverse directions, the quantization errors will not only be magnified but will also spread in both directions due to error propagation. In traditional wavelet-based ECG data compression methods, the error propagation effect of high octaves is the main factor that causes information rapidly lost in high CR situations.

In this paper, a reversible round-off 1-D NRDPWT, which associates the 1-D NRDPWT and the RROLT theorem, is derived for overall stages decomposition that obtains a DC value in the termination level and the wavelet coefficients of all octaves. The 1-D NRDPWT with unitary property can resist the quantization error propagation in both directions. The RROLT theorem shows that for an arbitrary invertible matrix, reversible transformation result with MDR property can be easily achieved by modifying the filter matrix with a scalar multiplication. The development of the reversible round-off 1-D NRDPWT is a generalized work of [18,19] where a special case of RROLT is presented to investigate the minimal register word length required for the realization of wavelet descriptor extraction.

Based on the reversible round-off 1-D NRDPWT, a novel ECG data compression method is proposed. In this approach, the RROLT theorem is applied to normalize the significance of each band's wavelet coefficients. This normalization mechanism facilitates the quantization scale analysis in a smaller searching space as compared with directly using original octave coefficients. Based on this analysis, a non-linear quantization algorithm is developed for ECG data compression. This algorithm attempts to keep the two performance parameters, CR and percentage root-mean-square difference (PRD), in linear relationship. This aim is achieved by providing high and low octave coefficients with small and large decimal quantization scales, respectively. For data coding, the quantized DC value and wavelet coefficients are encoded respectively by DPCM and the SPIHT algorithm in a non-loss way. By using the MIT-BIH arrhythmia database [20], sampled at 360 samples/s and with 11 bits/sample resolution for each signal. The comparison with the SPIHT scheme shows that the PRD is improved by 18.65% for $4 \leq \text{CR} \leq 12$ and 18.39% for $14 \leq \text{CR} \leq 20$.

This paper is organized as follows: in Section 2, the 1-D NRDPWT is presented. The RROLT theorem and the reversible round-off 1-D NRDPWT are developed in Section 3. The ECG data compression system based on the reversible round-off 1-D NRDPWT is proposed in Section 4. Several experiments of ECG data compression are shown in Section 5. Finally, discussions and conclusions are included in Section 6.

2. The non-recursive 1-D discrete periodized wavelet transform

Resisting error propagation is an effective method able to reduce the word-length-growth effect. To achieve this aim, non-recursive filters of overall stages are desired. For simplicity, we apply the matrix form 1-D DPWT [21] to derive non-recursive filters instead of directly synthesizing the filter coefficients in recursive decomposition process.

Given a negative integer J, $-J$ is referred to the decomposition levels. Let $N=2^{-J}$ denote the number of the original sampled data of a finite 1-D signal. For instance, when $N=64=2^{-(-6)}$, the overall stages decomposition will involve 6 decomposition levels. Let the N-dimensional column vectors $\mathbf{h}=[h_0,\ h_1,\ \ldots,\ h_{N-1}]^{\mathrm{t}}$ and $\mathbf{g}=[g_0,\ g_1,\ \ldots,\ g_{N-1}]^{\mathrm{t}}$ represent the low-pass and high-pass filters, respectively. The elements of $\mathbf{h}$ will satisfy the Daubechies' constrain, while $\mathbf{g}$ is given by a homeomorphic high-pass filter [21]. The vectors $\mathbf{h}$ and $\mathbf{g}$ derived from three Daubechies' filters (Daub4, Daub6, and Daub8, respectively, corresponding to tap = 4, 6, and 8) are shown in Table 1. By introducing an $N \times N$ matrix $\mathbf{T}$ such as

$$\mathbf{T} = \begin{bmatrix} 0 & 1 \\ \mathbf{I}_{N-1} & 0 \end{bmatrix}$$

where $\mathbf{I}_{N-1}$ is the $(N-1)\times(N-1)$ identity matrix, we can define the low-pass filter matrix $\mathbf{H}=[\mathbf{T}^0\mathbf{h},\ \mathbf{T}^2\mathbf{h},\ \ldots,\ \mathbf{T}^{N-2}\mathbf{h}, \mathbf{T}^{N}\mathbf{h}, \mathbf{T}^{N+2}\mathbf{h}, \ldots, \mathbf{T}^{2N-2}\mathbf{h}]$ and high-pass filter matrix $\mathbf{G}=[\mathbf{T}^0\mathbf{g}, \mathbf{T}^2\mathbf{g}, \ldots, \mathbf{T}^{N-2}\mathbf{g}, \mathbf{T}^{N}\mathbf{g}, \mathbf{T}^{N+2}\mathbf{g}, \mathbf{T}^{2N-2}\mathbf{g}]$ for the 1-D RDPWT. Let $\mathbf{s}_J=[s_J[0], s_J[1], \ldots, s_J[\mathrm{N}-1]]$ be the original sampled data of a finite 1-D signal. For $0 \geq j \geq J$, let $\boldsymbol{s}_j$ and $\mathbf{d}_j$ denote the scaling and wavelet coefficients of the jth level, respectively. Then $\boldsymbol{s}_j$ and $\mathbf{d}_j$ can be obtained from $\boldsymbol{s}_{j-1}$ with

$$\mathbf{s}_j = \mathbf{s}_{j-1}\mathbf{H} \quad \text{and} \quad \mathbf{d}_j = \mathbf{s}_{j-1}\mathbf{G}. \tag{1}$$

These two equations are the recursive form of the 1-D RDPWT, where both $\mathbf{H}$ and $\mathbf{G}$ contain 2 cycles of column