A Modified Run-Length Coding for the Realization of Wavelet-based ECG Data Compression System

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Abstract

With high compression performance, realization of wavelet-based data compression system is crucial for multi-lead ECG signal recording. In this paper, a modified run-length coding (MRLC) algorithm associated with an efficient quantization scheme is proposed for the realization of a RRO-NRDPWT-based ECG data compression system. The MRLC with regularity and low computational complexity is suitable for hardware implementation at a cost of compression performance. This sacrifice will be compensated by the new quantization scheme. By using the MIT-BIH arrhythmia database, the experimental results show that the proposed scheme can be competitive to other wavelet-based approaches in compression performance. In addition, the MRLC can improve traditional run-length coding by about 13%.

Keywords: Data compression, Wavelet transform, ECG

1. Introduction

Electrocardiogram (ECG) is a non-invasive modality that senses the electric action of heart motion from body surface. Since the heart is a three-dimensional organ, heart disease diagnosis usually needs the use of several ECG signals sensed from different positions around the heart. Typical requirement for heart disease diagnosis and health care is a long-term record of 12-lead ECG signals [1]. To this end, some portable ECG sensing systems associated with wireless data transmission have been developed for ambulatory monitoring and recording. ECG data compression is crucial for power consume reduction, efficient data transmission and storage [2-3].

Among many ECG data compression methods, wavelet-based approaches have attracted much attention from researchers due to high compression performance [3-7]. These approaches trying to optimize the compromise between compression ratio (CR) and distortion all belong to lossy compression method where the percentage root-mean-square difference (PRD) is usually used as the distortion measure. Lossy ECG data compression can be meaningful only if clinical information and the quality of reconstructed data can be preserved and maintained, respectively. For these sakes, hardware realization of wavelet-based data compression is crucial for efficiently real-time recoding of multi-lead ECG signals. For realization, it is desirable to select a method with high compression performance, low complexity, and fast convergence in reconstruction quality control.

Satisfying low complexity, threshold-based scheme [3, 4, 7-9] can be one optimal option. In [3], thresholding is first used to keep fixed percentage of wavelet coefficients at zeros and followed by an entropy coding. The filter bank-based method [7] uses a target PRD as the criterion for threshold value determination. Incorporating thresholding into a hierarchical tree coding, SPIHT scheme [4] can obtain excellent compression performance at the cost of coding complexity [7]. Recently, a novel wavelet-based approach [9] using orthogonal filters was proposed for efficient ECG data compression. This approach combines non-recursive 1-D discrete periodized wavelet transform (1-D NRDPWT) with the reversible round-off linear transformation (RROLLT) theorem to eliminate word-length-growth effect. The new DPWT process referred to as the 1-D RRO-NRDPWT facilitates real-time process and a design of linear distortion control. The RRO-NRDPWT-based ECG data compression also applied the SPIHT scheme for the coding of quantized wavelet coefficients.
SPIHT scheme is an efficient coding for the data inherent in hierarchical self similarities. However, this scheme exploits the self similarities in terms of dynamic data structures that will impose practical limitation on hardware implementation [10], especially for large-size data sequence. In this paper, for the realization of RRO-NRDPWT-based ECG data compression system, a modified run-length coding is presented instead of the SPIHT scheme. The run-length coding can effectively reduce computational complexity at the cost of compression performance. For compensation, a modified quantization scheme with approximately linear distortion is also presented for improving compression performance. By using the MIT-BIH arrhythmia database [11], several experiments are taken for compression performance evaluation.

2. A Non-Linear Quantization Scheme with Approximately Linear Distortion Characteristic

In this section, based on the 1-D RRO-NRDPWT, an efficient quantization scheme is developed. This scheme using truncation process in stead of the round-off method [9] can obtain better compression performance. The quantization scales will be searched in a local areas with the values found in [9] as the centroids. In addition, the quantization scales design is conducted with three criteria: 1) determining the quantization scales of all levels with a single variable QF, 2) maintaining the three variables: PRD, CR, and QF, in linear relationship, and 3) minimizing the gradient of the PRD-CR curve.

Let $d_j^*$ be a vector encompassing reversible wavelet coefficients of the $j$th level. The quantization process can be defined as

$$\tilde{x}_0^* = tr \left( \frac{s_0^*}{b_{DC}} \right)$$
$$\tilde{d}_j^* = tr \left( \frac{d_j^*}{c_j} \right),$$

where $tr(d_j^*)$ denotes the truncation process that truncates each element of $d_j^*$ to an integer, and $b_{DC}$ and $c_j$ are quantization scales of the $j$th level. In the inverse quantization process, each retrieved datum will be compensated by half of the quantization scale, namely:

$$\tilde{x}_0^* = b_{DC} \left( \tilde{x}_0^* + 0.5 \cdot sign(\tilde{x}_0^*) \right)$$
$$\tilde{d}_j^* = c_j \left( \tilde{d}_j^* + 0.5 \cdot sign(\tilde{d}_j^*) \right),$$

where $sign(\tilde{d}_j^*)$ denotes the sign vector of $\tilde{d}_j^*$. For the determination of quantization scales, we define $c_j$ as

$$c_j = \frac{cp[j]}{SNF_j},$$

where $SNF_j = \max_l \left\{ \sum_{k=2^l}^{2^{l+1}} |a_k'| \right\}$ is the significance normalization factor and $cp[j]$ are adjustable parameters given in the following.

$$cp[0] = b_{DC} = 0.1 + \frac{q}{10}, \ cp[-1] = 0.1 + \frac{q}{7},$$
\[ cp[-2] = 0.4 + \frac{q}{4}, \quad cp[-3] = 0.5 + \frac{q}{2} \quad \text{and} \]

\[ cp[j] = \left( 0.5 + \frac{q}{2} \right) \cdot (1.2)^{(j+4)} - (j+3) \cdot \frac{q}{2} \]

for \( j = -4, -5, \ldots, J + 1. \) (4)

where \( q = 10 \cdot \left( (QF + 1)/16 \right)^2 \) and \( QF \) is a variable available for desired PRD and CR control.

In order to explore the linear control performance of \( QF \), all 48 ECG signals recorded in the MIT-BIH arrhythmia database were investigated. Each signal contains about a 15 min length of sampled data. The measurement results are depicted in Fig. 1. Fig. 1 reveals that an approximately linear relationship between PRD and \( QF \) can be obtained for all signals with different gradients. Linear distortion property will facilitate a fast reconstruction quality control.

![Figure 1. The PRD-QF curves of 48 ECG signals derived by the modified quantization scheme](image)

**3. The Proposed ECG Data Compression Scheme**

The proposed RRO-NRDPWT-based ECG data compression scheme with the modified run-length coding is shown in Fig. 2. In encoding process, the 1-D RRO-NRDPWT first produces reversible wavelet coefficients \( \tilde{d}_j \). By (1), we can obtain the quantized data \( \tilde{d}_j \) for given a \( QF \) value. Finally, \( \tilde{d}_j \) will be losslessly encoded with the modified run-length encoding process described in the following:

**Step1:** Divide the quantized wavelet coefficients into eight encoding blocks, namely,

- Block_0: \( c_0, d_0, d_1, d_2 \)
- Block_1: \( d_4 \)
- Block_2: \( d_6 \)
- Block_3: \( d_8 \)
- Block_4: \( d_{10} \)
- Block_5: \( d_{12} \)
- Block_6: \( d_{14} \)
- Block_7: \( d_{16} \)

where the length of each block, \( z_i \) are 8, 8, 16, 32, 64, 128, 256, and 512 respectively.
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Step 2: Find the max word length of coefficients, \( n_{\text{max}} \), for each encoding block where \( \text{coe}_i \) denote the coefficients in block \( i \).

If \( \max(\text{abs(coe}_i)) = 0 \)

\[ n_{\text{max}} = 0 \]

else

\[ n_{\text{max}} = \lceil \log_2(\max(\text{abs(coe}_i))) \rceil + 1 \]

end

Step 3: Encode eight encoding blocks, respectively.

If \( n_{\text{max}} = 0 \)

Skip this block.

else

If \( \text{coe}_i \) is a non-zero coefficient

\( n_{\text{max}} \) bits are recorded in RL-set, and a sign bit is recorded in sign-set,

else

\( n-1 \) value, \( n \) consecutive zeros followed by \( \text{coe}_i \) is recorded with \( \lceil \log_2(z_i - 1) \rceil \)bits.

end

end

Step 4: Output sequence in the order of \( n_{\text{max}}_{i=0:7}, \text{RL-set}_{i=0:7}, \text{sign set}_{i=0:7} \).

For decoding, the inverse run-length coding is described in the following:

Step 1: Decode eight encoding blocks, respectively.

If \( n_{\text{max}} = 0 \)

Decode all coefficients of Block \( i \) as zero.

else

If the value of \( n_{\text{max}} \) bits is non-zero

Decode the value of \( n_{\text{max}} \) bits as \( \text{coe}_i \).

else

Decode \( \text{coe}_i \) and the following \( \lceil \log_2(z_i - 1) \rceil \) bits as \( n+1 \) consecutive zeros, where \( n \) is the value of \( \lceil \log_2(z_i - 1) \rceil \) bits.

end

end

After generating \( z_i \) coefficients, start the decoding process of Block \( i+1 \).

Step 2: After eight encoding blocks are decoded, correct the sign of each non-zero \( \text{coe}_i \) with the remaining bits in the sequence.

After the inverse run-length coding, the reconstructed data \( \hat{S}_f \) can be obtained by applying the inverse quantization process, eq. (2), and the inverse 1-D RRO-NRDWT in sequence where \( QF \) will be coded with DPCM scheme.
Figure 2. The RRO-NRDPWT-based ECG data compression scheme with run-length coding

4. Experimental Results

For hardware realization, complexity reduction usually leads to a sacrifice of CR. Several experiments were taken for quantitatively evaluating the compression performance of using the modified run-length coding. For simplicity, the original scheme of [9] and the proposed scheme are referred to as NRDPWT-6r and NRDPWT-RLC, respectively. A dataset that comprises 11 ECG signals: 100, 101, 102, 103, 107, 109, 111, 115, 117, 118, and 119, recorded in the MIT-BIH arrhythmia database (360 samples/sec and 11 bits resolution) was built. Each signal contains about a 10-min length of sampled data. Every segment involves 1024 samples of ECG data. The experimental result is shown in Fig. 3 where each value denotes the average PRD for a specified CR. The value of PRD is defined with

\[
PRD(\%) = \frac{\sum_{i=1}^{N}(s_j[i] - \hat{s}_j[i])^2}{\sum_{i=1}^{N}(s_j[i])^2} \times 100, \quad \text{(5)}
\]

where \(\hat{s}_j[i]\) and \(s_j[i]\) denote the reconstructed and original signal, respectively. Fig. 3 shows that for CR > 8, the NRDPWT-RLC can be competitive to SPIHT scheme [4]. For CR < 8, the difference of average PRD between NRDPWT-6r and NRDPWT-RLC can be within 1%.

Figure 3. A comparison of the three methods SPIHT [4], NRDPWT-6r [9] and NRDPWT-RLC
By using all the 48 records in the MIT/BIH arrhythmia database, the second dataset comprises the first 10-min length sampled data of each signal. A comparison with other wavelet-based approaches was shown in Table 1 where BFP-RLE [7] uses traditional run-length coding. Comparing with BFP-RLE scheme, NRDPWT-RLC can improve the average PRD by \((4.785 - 4.1525) / 4.785 \times 100 \approx 13.22\%\). And the NRDPWT-RLC is also competitive to other approaches.

Several compression results with the NRDPWT-RLC scheme are demonstrated in Fig. 4 where each signal involves first 2048 samples. Fig. 4(a) is the ECG signal of record 117 that has nice waveform. For this signal, the PRD can be lower than 3\% when CR reaches 22.2. The signal of record 232 with distorted and noisy waveform is shown in Fig. 4(b) where the reconstruction error can be unobservable. The ECG signal shown in Fig. 4(c) is the record 109 that has a waveform with baseline wandering and slight noise coupling. This signal has poor PRD due to the smoothing effect of quantization process. However, the clinical information including the amplitude and duration can be preserved well.

**Table 1.** PRD (%) comparison of several wavelet-based ECG data compression schemes by using 48 ECG signals in the MIT-BIH arrhythmia database. Part of data are cited from [7]

<table>
<thead>
<tr>
<th>Compression Method</th>
<th>CR</th>
<th>6:1</th>
<th>9:1</th>
<th>12:1</th>
<th>15:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIHT (K=(\sqrt{2})) [4]</td>
<td>2.82</td>
<td>4.04</td>
<td>5.17</td>
<td>6.89</td>
<td></td>
</tr>
<tr>
<td>VQ-DCCR (K=(\sqrt{2})) [6]</td>
<td>2.50</td>
<td>3.50</td>
<td>4.62</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td>BFP-RLE (K=(\sqrt{2})) [7]</td>
<td>2.81</td>
<td>4.17</td>
<td>4.66</td>
<td>7.50</td>
<td></td>
</tr>
<tr>
<td>NRDPWT-RLC</td>
<td>2.69</td>
<td>3.60</td>
<td>4.59</td>
<td>5.73</td>
<td></td>
</tr>
</tbody>
</table>

(a) The original and reconstructed ECG signal of MIT-BIH record 117
5. Conclusions

For realizing the RRO-NRDPWT-based ECG data compression system, a modified run-length coding algorithm has been proposed for replacing the SPIHT scheme. The new coding algorithm with regularity and low computational complexity is efficient for hardware implementation. Combing a multi-rate quantization scheme, a new wavelet-based ECG data compression method was also proposed. Several experimental results showed that the new ECG data compression scheme can be competitive to other wavelet-based approaches.

6. References

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