Evaluating transform-based compression techniques for electrocardiogram signals in clinical healthcare

Om Dev Rewar[#1], Er. Satnam Singh Dub[*2]

[#]M. tech Scholar, ECE Department, SSCET, Badhani, Punjab
**HOD, ECE Department, SSCET, Badhani, Punjab*

Abstract

Healthcare systems increasingly rely on continuous patient monitoring via electrocardiogram (ECG) signals. To optimize these frameworks, ECG data is typically collected and uploaded to cloud platforms for subsequent diagnostic analysis. However, transmitting these large datasets demands substantial internet bandwidth. To mitigate storage and transmission constraints, data compression techniques are vital. This paper delivers a comprehensive evaluation of transform-based ECG compression methodologies, highlighting their respective advantages and limitations. Using the standard MIT-BIH arrhythmia database for validation, we assess the performance of various transform techniques across a diverse set of signal profiles.

Keywords: Electrocardiogram (ECG), Internet of things (IoT), Compression ratio (CR), Percentage root mean square difference (PRD), Discrete wavelet transform (DWT).

1. Introduction

Electrocardiography (ECG) is a fundamental clinical procedure that records the heart's electrical activity over time via multiple electrodes attached to the patient's skin. These sensors detect minute cutaneous electrical fluctuations generated by the depolarization of the cardiac muscle during each cardiac cycle. As a result, the ECG remains an indispensable diagnostic instrument for monitoring and evaluating cardiovascular health. However, because ECG data is typically captured over extended durations at high sampling resolutions, it is inherently data-intensive [1].

Consequently, managing this information creates significant challenges, specifically demanding substantial storage capacity for archiving databases and high network bandwidth for real-time, remote tele-health analysis. Consequently, efficient data reduction methodologies are essential to lower storage overhead and enable seamless, real-time transmission without compromising clinical accuracy [2].

In a healthy heart, this rhythm presents as a predictable sequence of distinct waveforms—specifically the P, Q, R, S, and T waves—each corresponding to a precise mechanical action of the cardiac muscle (as illustrated in Figure 1). The P wave represents the initial upward deflection, while the subsequent Q, R, and S waves collectively form the QRS complex. Finally, ventricular repolarization generates the T wave, which is characterized by its characteristically smooth morphology [3].

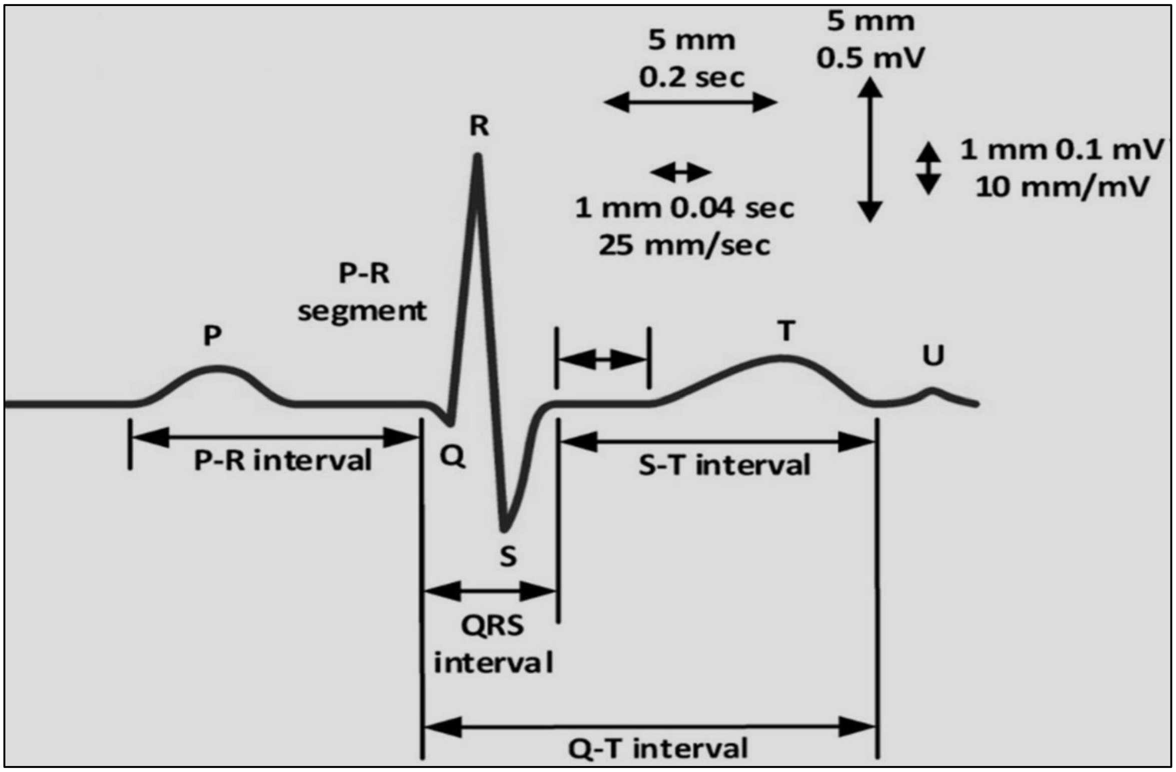

Figure 1: Typical ECG signal

The efficacy of an ECG data compression algorithm is typically evaluated using the following performance metrics [4]:

- **Compression Ratio (CR):** This metric represents the ratio between the uncompressed data size and the compressed data size. It serves as an absolute measure of data reduction, independent of external variables such as sampling frequency, signal bandwidth, ADC resolution, error thresholds, word length, lead configurations, database scale, or background noise. It is mathematically expressed as:

$$CR = \frac{\text{Original File Size}}{\text{Compressed File Size}}$$

A higher CR indicates a smaller compressed file size and greater storage efficiency.

- **Percentage Root Mean Square Difference (PRD):** This parameter quantifies the signal distortion and information loss introduced during the compression-decompression cycle. By measuring the variance between the source and the reconstructed waveforms, it assesses clinical fidelity. The PRD is calculated using the following formula:

$$PRD = \sqrt{\frac{\sum (X_i - \hat{X}_i)^2}{\sum X_i^2}}$$

Where X_i represents the original signal samples and $\hat{X}_i$ denotes the corresponding reconstructed signal samples.

2. Discrete Cosine Transform (DCT) based Compression

Among transform-based methodologies, the Discrete Cosine Transform (DCT) is widely adopted for Electrocardiogram (ECG) signal compression. By mapping the time-domain ECG waveform into the frequency domain, this approach isolates and eliminates statistical redundancies while preserving vital clinical morphology. Typically, ECG data exhibits high periodicity, characterized by prominent low-frequency components such as stable baselines and smooth T waves, interspersed with rapid, high-frequency transitions like the QRS complex [5, 6].

Initially, the continuous, time-domain ECG signal is partitioned into localized, uniform segments or windows. The DCT is then computed for each discrete block, a mathematical operation that decomposes the time-domain waveform into a linear combination of sinusoids at varying frequencies. A defining trait of the DCT is its exceptional energy compaction property: the vast majority of vital signal energy is concentrated into a minimal set of low-frequency coefficients. Conversely, high-frequency components which typically signify noise or fine-grained variations yield coefficients approaching zero. By applying a predefined threshold, these negligible high-frequency coefficients are zeroed out, and the remaining dominant parameters are quantized to optimize storage efficiency [7].

Finally, the Inverse DCT (IDCT) is executed to synthesize the compressed data back into its original time-domain waveform for clinical review.

3. Discrete Wavelet Transform (DWT) based Compression

The Discrete Wavelet Transform (DWT) represents a highly proficient, state-of-the-art methodology for the compression of Electrocardiogram (ECG) signals. In contrast to conventional frameworks like the Discrete Cosine Transform (DCT) which evaluate waveforms exclusively within the frequency domain, the DWT introduces dual time-frequency localization. Consequently, it simultaneously maps both the spectral components of the cardiac cycle and their precise temporal occurrences, rendering it exceptionally well-suited for capturing the inherently dynamic and non-stationary characteristics of ECG data [8, 9]. Rather than employing rigid sinusoidal waveforms, the DWT decomposes the ECG signal using translated and dilated iterations of a prototype function known as the mother wavelet. In cardiac signal processing, Daubechies or Symlet wavelets are frequently selected because their morphological structures closely mirror the natural geometric profile of a heartbeat [10].

The continuous ECG waveform is processed through a complementary pair of high-pass and low-pass filters. The low-pass filter extracts the low-frequency components, generating approximation coefficients (A_n) that represent large-scale baseline trends and smooth T-wave behaviors. Concurrently, the high-pass filter captures abrupt, high-frequency transient details such as the rapid deflections of the QRS complex and clinical anomalies, producing detail coefficients (D_n) [11]. This decomposition scheme is executed iteratively upon the successive approximation coefficients, yielding a multi-resolution analysis of the signal. Because minor fluctuations and background noise map to the detail coefficients, data reduction is achieved by applying either hard or soft thresholding functions to eliminate parameters below a specific tolerance level [12, 13]. Ultimately, the Inverse Discrete Wavelet Transform (IDWT) reverses this architectural pipeline, mathematically synthesizing the retained coefficients to reconstruct the original time-domain ECG signal.

4. Results

A joint compression framework incorporating both DCT and DWT techniques was implemented to optimize ECG data storage while safeguarding vital clinical features during reconstruction. The correlation between the baseline waveform and the resulting normalized, reconstructed signal is depicted in Figures 2.

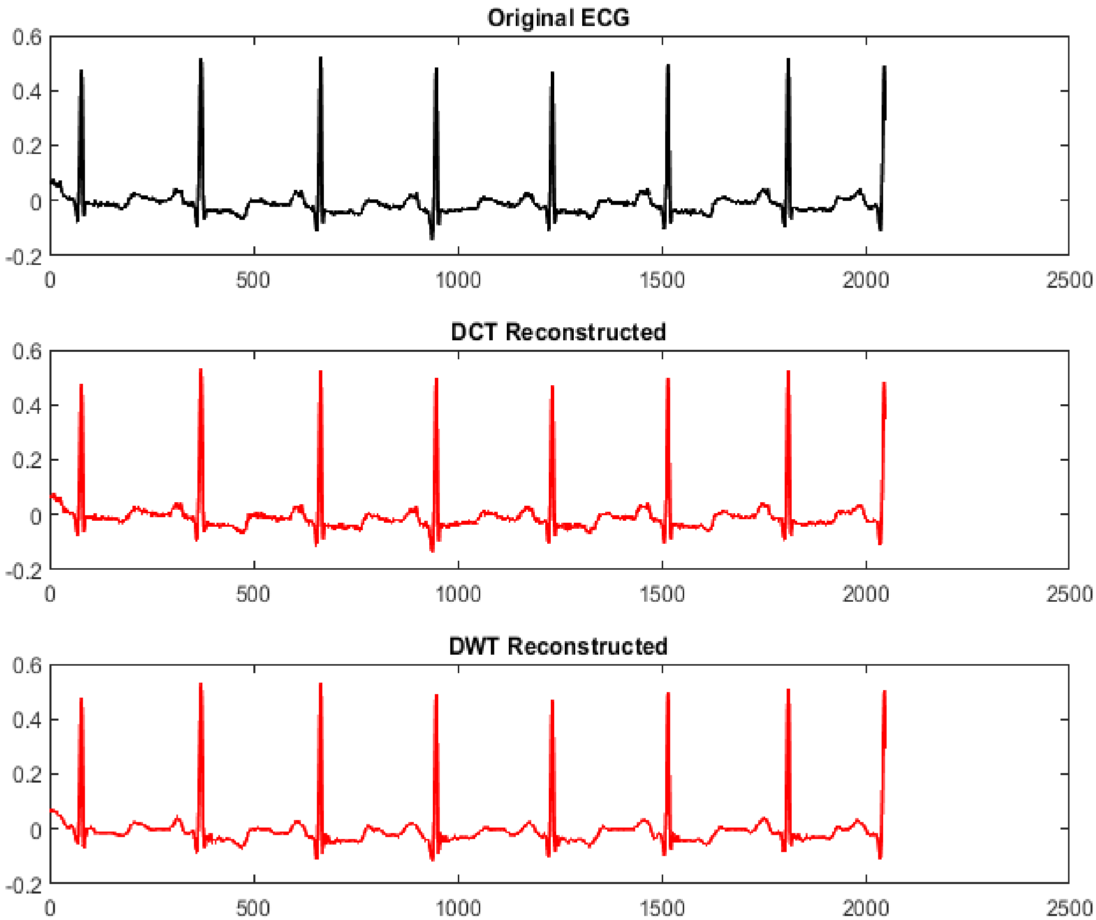

Figure 2: Original and reconstructed ECG waveform of MIT-BIH record 100

The compression performance benchmarks for both the DCT and DWT techniques are presented in Table 1, evaluated across various data records obtained from the MIT-BIH arrhythmia database.

Table 1: Performance of DCT and DWT based ECG signal compression

Record	Method	Performance Metrics		
		CR	PRD	PRDN
100.dat	DCT	4.179	6.088	6.096
	DWT	11.636	10.006	10.020
103.dat	DCT	6.168	7.504	7.534
	DWT	10.449	4.915	4.934
108.dat	DCT	11.315	11.559	12.404
	DWT	10.449	9.484	10.176
113.dat	DCT	5.936	7.425	7.675
	DWT	10.039	3.634	3.756
118.dat	DCT	7.367	8.816	9.457
	DWT	8.063	7.103	7.619

123.dat	**DCT**	5.333	5.040	5.208
	DWT	10.952	5.835	6.028
201.dat	**DCT**	5.885	4.870	4.875
	DWT	11.191	7.238	7.244
208.dat	**DCT**	7.447	6.547	6.556
	DWT	10.836	5.249	5.257
228.dat	**DCT**	9.184	12.894	15.227
	DWT	5.347	6.189	7.309
234.dat	**DCT**	7.938	9.895	11.311
	DWT	9.706	5.146	5.883
Average	**DCT**	7.0752	8.0638	8.6343
	DWT	9.8668	6.4799	6.8226

Figure 3 presents a performance comparison between DCT and DWT-based ECG compression techniques, evaluating CR, PRD, and PRDN averaged across ten distinct ECG signals.

As illustrated in Figure 3, the DWT method outperforms the DCT approach. Specifically, DWT yields a higher compression ratio (CR) alongside lower PRD and PRDN metrics than DCT.

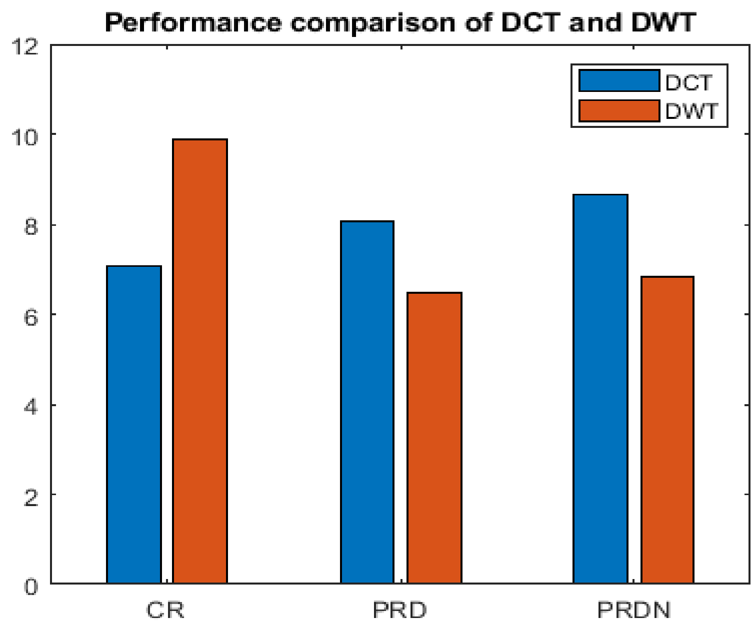

Figure 3: Quality assessment of DCT vs DWT based ECG signal Compression

5. Conclusion

Electrocardiogram (ECG) analysis serves as a critical diagnostic approach for identifying cardiovascular anomalies. This study investigates transform-domain frameworks tailored for ECG data compression in medical applications. Specifically, we evaluate and compare the performance of the Discrete Cosine Transform (DCT) and the Discrete Wavelet Transform (DWT). The findings indicate that wavelet-based compression offers substantial advantages over DCT and alternative methods, as the DWT framework yields a remarkably high compression ratio while ensuring superior structural fidelity during signal reconstruction.

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