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A Study on ECG Signal Compression Techniques Using Discrete Wavelet Transform

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Abstract

Electrocardiogram (ECG) signal compression has become an essential area of research due to the exponential growth of digital healthcare, wearable monitoring devices, and telemedicine applications that generate and transmit large volumes of ECG data. Efficient compression techniques are required to reduce storage and transmission demands while preserving the diagnostic quality of clinically significant features such as the P wave, QRS complex, and T wave. Among various approaches, the Discrete Wavelet Transform (DWT) has emerged as one of the most effective methods, owing to its capability for multi-resolution analysis, energy compaction, and superior time-frequency localization. Numerous DWT-based techniques have been developed, including wavelet thresholding, embedded zerotree coding, SPIHT, and hybrid entropy-based methods. This survey provides a comprehensive overview of these techniques, focusing on their principles, performance metrics such as Compression Ratio (CR), Percentage Root Mean Square Difference (PRD), and Signal-to-Noise Ratio (SNR), while also highlighting challenges, clinical relevance, and potential future research directions.

Keywords: ECG signal compression, Discrete Wavelet Transform (DWT), Compression Ratio (CR), Percentage Root Mean Square Difference (PRD), Telemedicine.

Introduction

Electrocardiogram (ECG) is one of the most widely used non-invasive diagnostic tools in the field of cardiology, providing vital information about the electrical activity of the heart and aiding in the detection and monitoring of various cardiac disorders. With the advancement of digital healthcare, wearable devices, and telemedicine, the continuous recording and transmission of ECG signals have become increasingly common, leading to the generation of vast amounts of data that require efficient storage, processing, and transmission. To address these challenges, ECG signal compression has emerged as a crucial technique, aiming to reduce data size while preserving clinically significant information essential for diagnosis. Among various compression methods, the Discrete Wavelet Transform (DWT) has gained prominence due to its ability to provide multi-resolution analysis and superior time-frequency localization, making it particularly suitable for non-stationary biomedical signals such as ECG. The DWT effectively concentrates the signal energy into a few significant coefficients, allowing for high compression ratios without losing diagnostic features such as the P wave, QRS complex, and T wave. Over the years, a variety of DWT-based ECG compression techniques have been proposed, including wavelet thresholding, set partitioning in hierarchical trees (SPIHT), embedded zerotree wavelet coding (EZW), and hybrid methods that integrate wavelet decomposition with entropy coders such as Huffman or arithmetic coding. Performance evaluation of these methods is generally carried out using metrics like Compression Ratio (CR), Percentage Root Mean Square Difference (PRD), Signal-to-Noise Ratio (SNR), and Quality Score (QS), ensuring a balance between efficiency and clinical reliability. Standard databases like the MIT-BIH Arrhythmia Database and PTB Diagnostic Database have been extensively used to benchmark and validate these methods. Despite significant progress, challenges remain in achieving real-time compression with minimal distortion, preserving diagnostic fidelity across diverse patient datasets, and optimizing computational complexity for wearable and remote monitoring applications. This survey aims to provide a comprehensive overview of DWT-based ECG compression techniques, critically analyzing their strengths, limitations, and clinical applicability, while also identifying gaps in existing research and highlighting future directions. By consolidating recent advancements and performance comparisons, the study contributes to the growing body of knowledge in biomedical signal processing and supports the development of efficient and reliable telecardiology systems.

Importance of Electrocardiogram (ECG) in Cardiac Healthcare

The Electrocardiogram (ECG) plays a fundamental role in cardiac healthcare as one of the most reliable and widely used diagnostic tools for evaluating the electrical activity of the heart. It provides a graphical representation of the heart's rhythm and conduction patterns, enabling physicians to detect abnormalities such as arrhythmias, ischemia, myocardial infarction, and other cardiovascular disorders at an early stage. Since cardiovascular diseases remain a leading cause of mortality worldwide, the importance of ECG in preventive, diagnostic, and therapeutic contexts cannot be overstated. ECG recordings allow for continuous monitoring, which is particularly crucial in intensive care units, during surgical procedures, and in long-term management of chronic heart conditions. With the growth of digital healthcare and wearable technologies, ECG monitoring has expanded beyond hospital settings into home-based and remote applications, supporting telemedicine and real-time healthcare delivery. Furthermore, ECG is non-invasive, cost-effective, and relatively simple to administer, making it accessible even in resource-limited settings. The interpretation of ECG waves, including the P wave, QRS complex, and T wave, provides clinicians with detailed insights into the functioning of the atria and ventricles, helping them assess both structural and functional cardiac health. Beyond diagnosis, ECG also aids in evaluating the effectiveness of treatments such as pacemakers, defibrillators, and pharmacological interventions, ensuring optimal patient outcomes. Modern

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advancements in digital signal processing have further enhanced the utility of ECG, enabling automated analysis, detection of subtle abnormalities, and integration into electronic health records. The vast amount of ECG data generated in continuous and ambulatory monitoring emphasizes the importance of efficient data handling, including compression techniques, to ensure accurate transmission and storage without compromising diagnostic integrity. Thus, the ECG not only serves as a cornerstone of clinical cardiology but also continues to evolve as a key component of personalized medicine, preventive healthcare, and advanced biomedical research. Its indispensable role in early detection, continuous monitoring, and management of heart diseases makes it an essential pillar of modern cardiac healthcare systems.

Overview of Signal Compression Metrics

In the field of biomedical signal processing, and particularly in electrocardiogram (ECG) data compression, the evaluation of compression algorithms relies heavily on standardized metrics that can effectively measure both the efficiency of data reduction and the preservation of clinically significant information. Among these, the Compression Ratio (CR), Percentage Root Mean Square Difference (PRD), Signal-to-Noise Ratio (SNR), and Quality Score (QS) are the most widely used. The Compression Ratio (CR) is defined as the ratio of the original data size to the compressed data size, mathematically expressed as CR = (Original Size) / (Compressed Size). A higher CR indicates better data reduction efficiency, which is desirable for storage and transmission in telemedicine and wearable healthcare devices. However, an excessively high CR may lead to information loss, which necessitates complementary metrics that evaluate distortion. The Percentage Root Mean Square Difference (PRD) is one such measure, quantifying the distortion between the original and reconstructed signals after compression. PRD is calculated by taking the root mean square error between the two signals, normalized by the energy of the original signal, and expressed as a percentage. A low PRD value indicates that the reconstructed signal is nearly identical to the original, which is critical for diagnostic accuracy. Clinically, a PRD value below 9% is often considered acceptable, although stricter thresholds (e.g., < 2%) are recommended for certain diagnostic applications where subtle waveform changes must be preserved. Alongside PRD, the Signal-to-Noise Ratio (SNR) is another key metric used to measure signal quality. SNR represents the ratio of the signal power to the noise power, typically expressed in decibels (dB). A higher SNR value implies that the reconstructed signal maintains high fidelity relative to the original, with minimal distortion introduced by compression. In practical terms, ECG compression algorithms aim to achieve SNR values greater than 20–30 dB to ensure clinically acceptable results. To better capture the trade-off between efficiency and accuracy, the Quality Score (QS) is often employed as a composite metric. The QS is usually defined as the ratio of CR to PRD, providing a balanced index that reflects how effectively an algorithm compresses data while maintaining low distortion. A higher QS value is indicative of an efficient method that reduces data volume without sacrificing diagnostic reliability. This metric is especially useful when comparing different compression techniques, as it provides a single parameter that accounts for both data reduction and reconstruction quality. Ultimately, clinical acceptability is determined not only by numerical performance but also by how well the reconstructed ECG retains diagnostic features such as the P wave, QRS complex, and T wave, which are vital for the detection of arrhythmias, ischemia, and other cardiac abnormalities. For this reason, compression methods must strive to maintain low PRD values and high SNR levels, ensuring that essential morphological characteristics of ECG signals remain intact. In conclusion, signal compression metrics such as CR, PRD, SNR, and QS form the backbone of performance evaluation in ECG data compression research, allowing for a systematic assessment of algorithms and guiding the development of methods that balance efficiency with clinical reliability.

Characteristics of ECG Signals

Electrocardiogram (ECG) signals are vital biomedical signals that represent the electrical activity of the heart as it contracts and relaxes during each cardiac cycle, and their unique characteristics make them highly valuable for clinical diagnosis and monitoring. One of the key characteristics of ECG signals is their periodicity, as they repeat in a cyclic manner corresponding to the heartbeats. Although the fundamental shape of ECG waveforms remains consistent, the cycle duration can vary depending on heart rate, autonomic activity, or pathological conditions. Another important characteristic is the amplitude variation of ECG signals, which reflects the strength of electrical activity in different phases of the cardiac cycle. These amplitude variations can be influenced by physiological conditions, electrode placement, noise interference, and disease states, making precise interpretation critical. Clinically, the ECG is characterized by distinct waveform components: the P wave, which represents atrial depolarization and provides insight into atrial function; the QRS complex, which corresponds to ventricular depolarization and is the most prominent feature of the ECG, essential for detecting arrhythmias, bundle branch blocks, or myocardial infarction; and the **T wave**, which indicates ventricular repolarization and is crucial in identifying ischemia, electrolyte imbalances, and other abnormalities. The accurate detection and analysis of these features are critical for diagnosis, as subtle changes in waveform morphology, amplitude, or timing can provide early indicators of cardiovascular diseases. Furthermore, ECG signals are often non-stationary in nature, meaning their frequency and amplitude characteristics may change over time due to varying physiological or pathological conditions. This non-stationarity makes ECG analysis challenging and necessitates advanced signal processing methods such as the Discrete Wavelet Transform (DWT), which can effectively capture both time and frequency information. Additionally, ECG signals are often contaminated with artifacts from muscle activity, respiration, or power-line interference, which

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further complicates their analysis and requires robust preprocessing. In summary, ECG signals are characterized by their periodicity, amplitude variations, and clinically significant features such as the P wave, QRS complex, and T wave, all of which carry essential diagnostic information and highlight the importance of accurate signal processing and interpretation in cardiac healthcare.

Discrete Wavelet Transform (DWT)

The Discrete Wavelet Transform (DWT) has emerged as one of the most effective tools for analyzing and compressing biomedical signals, particularly electrocardiogram (ECG) signals, because of its unique ability to represent data in both time and frequency domains simultaneously. At its core, the DWT is based on the principle of multi-resolution analysis, which decomposes a signal into different frequency bands while preserving temporal information. Unlike traditional Fourier analysis, which provides only frequency-domain information and assumes signal stationarity, the DWT offers time-frequency localization, enabling the identification of transient events and localized variations that are common in non-stationary signals such as ECG. This property is especially significant because ECG waveforms, composed of the P wave, QRS complex, and T wave, are inherently non-stationary, and their diagnostic value lies in subtle temporal and morphological variations that must be preserved during compression.

One of the major advantages of DWT over classical Fourier or short-time Fourier transform (STFT) methods is its adaptability in analyzing signals at different scales. While Fourier transforms lose time information and STFT suffers from fixed window limitations, the DWT uses variable-sized windows—narrow for high-frequency components and wide for low-frequency components—allowing it to efficiently capture both sharp details, such as the QRS complex, and smooth, long-duration components like the P and T waves. This multi-resolution capability makes DWT highly suitable for ECG analysis where both fine and coarse features carry diagnostic significance.

For compression, the DWT is particularly effective because of its ability to achieve energy compaction, meaning that most of the signal's energy is concentrated in a small number of significant wavelet coefficients, while the remaining coefficients carry minimal or redundant information. By retaining only the most relevant coefficients and discarding or quantizing the less significant ones, substantial data reduction can be achieved without compromising clinically essential features. This ensures that diagnostic quality is preserved even at high compression ratios. Additionally, the hierarchical decomposition structure of DWT lends itself naturally to advanced compression techniques such as embedded zerotree wavelet (EZW) coding, set partitioning in hierarchical trees (SPIHT), and hybrid entropy coding methods, further enhancing its efficiency. The DWT stands out as the preferred method for ECG compression because it not only reduces data size effectively but also preserves critical diagnostic features through multi-resolution analysis and time-frequency localization. Its superiority over Fourier-based methods, coupled with its ability to compact energy and retain morphological details, makes it an indispensable tool for modern biomedical signal processing, particularly in applications like telemedicine, portable monitoring, and long-term cardiac data storage.

Conclusion

The survey on ECG signal compression techniques using the Discrete Wavelet Transform (DWT) highlights the crucial role of efficient data reduction methods in modern cardiac healthcare, particularly in the era of digital medicine, wearable monitoring devices, and telemedicine applications. ECG signals, being non-stationary and clinically significant, demand compression techniques that balance high compression ratios with minimal distortion to ensure diagnostic integrity. The DWT proves to be exceptionally effective in this context due to its multi-resolution analysis, superior time-frequency localization, and energy compaction properties, which enable it to retain critical morphological features such as the P wave, QRS complex, and T wave even at high levels of compression. Various DWT-based methods, including wavelet thresholding, embedded zerotree wavelet (EZW), set partitioning in hierarchical trees (SPIHT), and hybrid approaches with entropy coding, have demonstrated strong performance when evaluated using standard metrics such as Compression Ratio (CR), Percentage Root Mean Square Difference (PRD), Signal-to-Noise Ratio (SNR), and Quality Score (QS). These methods consistently show that DWT not only reduces storage and transmission requirements but also maintains clinically acceptable signal fidelity, making it highly suitable for real-time and remote healthcare systems. However, challenges remain in optimizing computational efficiency for resource-constrained devices, minimizing distortion across diverse patient populations, and ensuring robustness against noise and artifacts that often contaminate ECG recordings. Future research directions may focus on integrating DWT-based compression with machine learning and adaptive coding strategies to further enhance efficiency, reliability, and clinical applicability. Additionally, hybrid frameworks combining wavelet transforms with advanced entropy coders or deep learning models hold promise for next-generation ECG compression systems. Overall, the survey underscores that DWT-based compression techniques provide a strong foundation for reliable and scalable ECG data management, bridging the gap between large-scale data acquisition and clinically meaningful interpretation, thereby supporting the advancement of personalized and accessible cardiac healthcare.

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