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# An ECG compression algorithm with guaranteed reconstruction quality based on optimum truncation of singular values and ASCII character encoding

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ABSTRACT

An efficient electrocardiogram (ECG) compression algorithm provides two-fold benefits: first, it enlarges the storage capability and second, it enhances the transmission efficiency of the communication-link in real-time tele-monitoring applications. Maintaining the quality of the reconstructed signal at a pre-determined level is a very important criterion of an ECG compression algorithm, but the area of such quality-guaranteed ECG signal compression is still lagging behind. This paper presents a high performance quality-guaranteed two-dimensional (2D) single-lead ECG compression algorithm using singular value decomposition (SVD) and lossless-ASCII-character-encoding (LLACE)-based techniques. At the pre-processing stage, the ECG signal is de-noised, and then the noise-free signal is down-sampled if the sampling frequency of the signal is found to be higher than that of a certain threshold. Then, the ECG R-peaks are detected using a Hilbert transform (HT)-based approach to extract ECG-beats. Extracted beats are arranged to form a 2D matrix, and then the matrix is decomposed using the SVD technique. An optimum number of singular values are retained in such a way that the quality of the reconstructed ECG signal would not be degraded from a pre-defined diagnostic ECG-feature-distortion measure. The truncated right singular matrix coefficients are quantized and encoded into ASCII characters, and the truncated left singular matrix coefficients are compressed using the LLACE-based technique. The SVD and LLACE methods exploit the strong inter-beat and inter-sample correlations, respectively, of an ECG signal to attain high compression performance. Evaluation results show that the mean-opinion-score of the reconstructed ECG signals signal falls under the category 'very good' as per the gold standard subjective measure.



## 1. Introduction

Electrocardiogram (ECG) is the graphical representation of heart's electrical activity recorded by means of electrodes from various standardized locations on the body surface, and is considered as the prime human physiological signal [1]. Due to the growing interest in healthcare system and management, the need for recording ECG signal has increased significantly in recent days [2], and as a consequence, the requirement of data storing capacity has also raised extensively. It requires about 1.45 MB computer memory to store 12-lead ECG data (or approximately 120 KB computer memory to store a single-lead ECG data) of 1-min duration sampled at 1 kHz rate and with a 16-bit resolution. Hence, the reduction of data size without jeopardizing the clinical morphology of the ECG signal has become indispensable. A reliable high-performance ECG compression algorithm could be a solution to compete with such a high growth rate of storage request.

A number of dedicated and efficient compression algorithms have been proposed for ECG signal over the past several decades. Based on the methodology, these algorithms could be broadly categorized into three major classes: direct, transformation-based and prediction-based. Each of these classes can again be divided into two sub-classes: lossless and lossy. For single-lead ECG, reduction in data size is basically achieved by exploiting two different types of correlations: inter-beat and inter-sample. Direct ECG compression algorithms [3–6] exploit the inter-sample correlation. Advantages of using direct compression schemes are that they usually require less computational resources and are easy to implement on real-time systems. In Ref. [3], Bera et al. proposed a direct compression algorithm for ECG signal, where each ECG-beat is divided into

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two blocks, namely, 'plain' and 'complex' using a threshold-based method and then, these two blocks are compressed using two different techniques. Similar types of ECG compression algorithms have also been proposed in Refs. [7] and [8]. On the other hand, transformation-based methods such as wavelet transform (WT) [9,10], Fourier transform (FT) [11,12], discrete cosine transform (DCT) [13] utilize their energy compaction property to achieve high compression performance. The theme of any transformation-based ECG compression algorithm is to convert the original signal into some other domain, then discard the comparatively less significant coefficients using a suitable threshold-based technique, and finally, encoding the rest of the coefficients. In [11], Sadhukhan et al. proposed a FT-based compression technique, where the coefficients of the ECG signal are calculated using the sine and cosine basis functions, and only a few of these coefficients are retained. The retained coefficients are then encoded using an adaptive bit-assignment scheme. The bit-assignment map is also encoded using the run length encoding (RLE) technique to enhance the compression performance. Among the WT-based methods, discrete wavelet transform (DWT) has gained the maximum popularity because of its good localization property of the signal components in time-frequency domain [14]. On the other hand, the parameter extraction-based methods are mainly based on linear and long term prediction algorithms [15,16]. Both the lossless and lossy compression techniques have a few advantages and disadvantages. The data reduction performance of a lossy method is always better than that of a lossless one, but the lossy method may lose some clinically significant information. On the other hand, in case of lossless compression, the reconstructed signal would be an exact replica of the original one, which is sometimes a strict requirement from the legal or clinical point of view [17].

A number of SVD-based single-lead ECG compression algorithms have been proposed exploiting the strong inter-beat correlations of the signal [18–23]. The suitability and advantages of using SVD in ECG signal processing, particularly in compression is well demonstrated by Wei et al. in Ref. [22]. An important feature of SVD is that it is able to extract the fundamental structural modes of a system, which can be used to analyze a signal exhibiting quasi-periodic nature such as ECG. SVD technique decomposes a 2D matrix into two orthonormal and one diagonal matrices. Elements of the diagonal matrix are in descending order of magnitude and are called the singular values. If the column/row-wise correlation of the data present in a 2D matrix is high, then most of the energy of the data is expected to be concentrated over the first few singular values. Therefore, the original data matrix can be approximated with a low and acceptable level of distortion by discarding the rest of the singular values. Since the ECG-beats (one complete cardiac-cycle is called a beat) are characterized by a periodic occurrence of different waves and segments, the correlation among the beats is high, which increases the probability of achieving a high compression performance using SVD. In Refs. [18] and [19], Kumar et al. proposed an SVD and adaptive scanning wavelet difference reduction (ASWDR)-based single-lead ECG compression technique, where the 1D ECG signal is converted into a 2D matrix through proper beat-detection and normalization. The matrix is then decomposed using the SVD technique, and the comparatively less significant singular values are discarded. The dimension-reduced matrix is then processed with the ASDWR coding technique to enhance the compression performance. A similar type of SVD and embedded zero tree wavelet (EZW)-based ECG compression technique is reported in Ref. [20]. Recently, Liu et al. proposed an SVD-based compression technique of encrypted ECG signal [23]. Here also, first, the 1D ECG signal is arranged into 2D, and then the matrix is multiplied by an orthogonal key-matrix of dimension $m$ x $m$ (where $m$ is the number of ECG-beats), which is generated randomly, and used only once. Then, the encrypted ECG matrix is decomposed using the SVD, and the resulting orthonormal and diagonal matrices' coefficients are compressed using the arithmetic coding technique. Removal of both high and low frequency noises, and also the performance of the beat detection technique are the two very important criteria for those 2D ECG compression algorithms whose performances depend on the correlation of the ECG-beats, such as the SVD-based methods [21]. The technique which is used for denoising and detecting the ECG-beats are not mentioned properly in [23]. It has also been shown in [23] that in most of the cases, the compression algorithm performs better on encrypted ECG data. Such an interesting result suggests that there is an increase in the correlation among ECG-beats due to encryption, but the reason is left unclarified.

In recent days, a new paradigm called compressed sensing (CS) is being extensively used in the field of on-node ECG acquisition and compression [2,24–31]. According to the CS theory, a small number of random, but linear measurements, are enough for the reconstruction of sparse signals [29]. Since the ECG signal is also sparse in nature, it can be acquired at a rate which is below that of the Nyquist. Therefore, the CS-based methods are able to reduce the sampling burden of the analog-to-digital converter of an ECG acquisition system and thereby achieve energy-saving and compression. But, the use of CS-based methods might not be suitable in all the cases due to their poor data reduction performances [58].

Guaranteeing or the ability of controlling the quality of signal reconstruction is an important criterion in developing a lossy type ECG signal compression algorithm. An ideal quality-guaranteed (QG) ECG signal compression algorithm should reproduce the signal with the same quality measure, which was defined/predicted earlier at the time of compression. A number of QG or quality-controlled (QC) ECG compression algorithms have been reported in the literature [32–40]. The advantages of using the principal component analysis (PCA) technique are exploited by Gupta in [32] for the compression of ECG signals. The PCA technique decomposes a matrix into another two matrices, one containing the principal components (PCs) and the other one containing the Eigen values. In Ref. [32], it has been shown that most of the energy of the ECG signal is concentrated over a few PCs. First, the 2D ECG-beat matrix is decomposed using the PCA technique, and a few PCs and eigenvectors are retained. Finally, the retained PCs and eigen vectors are compressed using a modified delta and Huffman coding (HC)-based techniques. The algorithm can be used in two different types of modes: (1) QC and (2) compression-controlled. In the QC mode, the algorithm is able to reconstruct the ECG signal with a low reconstruction error, but the compression performance is considerably poor. On the other hand, in the compression controlled-mode, the algorithm achieves an attractive compression performance, but the reconstruction error is too high for the clinical evaluation. In Ref. [33], a nearly-perfect reconstruction cosine-modulated-filter-bank (N-PR CMFB), and HC-based QG compression algorithm for ECG signal is proposed. The algorithm offers a low signal reconstruction error. Chen et al. proposed a wavelet transform and Lempel-Ziv-Welch encoder-based QG ECG compression algorithm in Ref. [36]. All of these aforementioned QC/QG ECG compression algorithms (except Ref. [40]) use the non-diagnostic distortion measures of ECG, e.g. percent root mean square difference (PRD), for controlling the quality of the reconstructed signals. Non-diagnostic measures are unable to characterize the distortions in local ECG waves and segments [40]. Moreover, the performance of an ECG compression algorithm strongly depends on the sampling rates of the signals [32] and hence, an ECG compression algorithm should be well tested at different sampling rates, and on various pathologies to be applicable in various types of applications including tele-healthcare and offline ECG systems.

Motivation behind the proposed research work is to develop a high performance QG ECG compression algorithm, which will be