Computers and Electrical Engineering 000 (2016) 1–16

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

Weighted mixed-norm minimization based joint compressed sensing recovery of multi-channel electrocardiogram signals☆

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ARTICLE INFO

Article history:
Received 28 March 2015
Revised 28 January 2016
Accepted 29 January 2016
Available online xxx

Keywords:
Multi-channel electrocardiogram
Compressed sensing
Weighted mixed-norm minimization
Discrete wavelet transform
Joint sparsity
Data compression

ABSTRACT

Computational complexity and power consumption are prominent issues in wireless telemonitoring applications involving physiological signals. Because of its energy-efficient data reduction procedure, compressed sensing (CS) emerged as a promising framework to address these challenges. In this work, a multi-channel CS framework is explored for multichannel electrocardiogram (MECG) signals. The work focuses on the successful joint recovery of the MECG signals using a low number of measurements by exploiting the correlated information across the channels. A CS recovery algorithm based on weighted mixed-norm minimization (WMNM) is proposed that exploits the joint sparsity of MECG signals in the wavelet domain and recovers signals from all the channels simultaneously. The proposed WMNM algorithm follows a weighting strategy to emphasize the diagnostically important MECG features. Experimental results on various MECG databases show that the proposed method can achieve superior reconstruction quality with high compression efficiency as compared to its non-weighted counterpart and other existing CS-based ECG compression techniques.

1. Introduction

Compressed sensing (CS) is an emerging signal processing technique that enables the acquisition of sparse signals in a small set of linear projections (called *measurements*) [1]. The size of measurement vector is much smaller than that of the original signal, but it still contains the required information for exact signal recovery. CS exploits the signal structure and enables signal acquisition at sub-Nyquist rate, directly outputting the compressed form of the signal. Consequently, the signal encoding becomes quite simple and energy-efficient in the CS framework. This feature of CS motivated its use in many resource-constrained applications [2–8]. In these applications, CS offers potential solutions to some of the major challenges, such as energy efficiency, computational complexity, memory usage, etc. Wireless body area network (WBAN)-enabled mobile electrocardiogram (ECG) telemonitoring is one such application where CS has been successfully used to reduce the energy consumption and complexity of the system [3–8]. For energy-efficient data reduction, CS-based WBAN applications exploit the inherent sparse nature of ECG signals either in the time domain [4,5], or wavelet domain [3,6–8]. Though, conventional wavelet-based ECG compression methods have higher data compression capability than CS-based

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Associate Editor Dr. M. R. Daliri.

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http://dx.doi.org/10.1016/j.compeleceng.2016.01.027

approaches, their data encoding cost is significantly higher [3]. Because of this, CS-based techniques emerged as an effective alternative to wavelet-based methods for WBAN applications.

In earlier studies, Mamaghanian et al. [3] established and quantified the potential of CS for low-complexity and energy-efficient data reduction in the WBAN-enabled ECG monitors. Various design considerations were studied by Dixon et al. [4] for the CS-based data acquisition and reconstruction systems. A block sparse Bayesian learning (BSBL)-based approach was employed by Zhang et al. [5] for the fetal-ECG telemonitoring applications. Recently, some techniques utilizing prior knowledge about ECG signals in the traditional CS reconstruction algorithms have been reported with improved results [6,7]. In the aforementioned works, the telemonitoring systems studied are limited to single channel ECG signals. However, multi-channel or multi-lead ECG (MECG) signals are preferred by cardiologists for detailed diagnosis [9]. Motivated by this, we present a study of the MECG signals in a joint CS framework, intended for the remote healthcare applications. The ECG signals acquired through different channels are not independent. Instead, they share mutual cardiac information common to all channels. The source of this information is the electrical heart vector. The projection of this vector in different directions leads to ECG signals in different channels. In such a scenario, channel-by-channel processing of MECG is not optimal in terms of the computational cost as well as the system performance. Hence, some novel unified CS-based approaches are required for the correlated MECG signals.

In the proposed work, the CS model is based on a multiple-measurement-vector (MMV) approach [10]. This is unlike the earlier models based on traditional single-measurement-vector (SMV) [3,4,7,8]. The MMV, or row-sparse modeling of the MECG signals, helps exploit the natural group sparsity of different channels, which is present because of their inherent correlated structure. Recently, the MMV approach has been used for the MECG signals in a CS-based joint compression work employing a mixed-norm minimization (MNM)-based signal recovery [11]. It is to be noted that when the number of measurements is low (at higher compression ratios), the performance of the algorithm was observed to be unsatisfactory. The amplitude dependence of the MNM algorithms, similar to traditional l_1-norm minimization algorithms, might be the reason behind this under-performance [12,13]. Due to the amplitude dependence, the nonzero rows corresponding to the higher coefficients in joint sparse representation are penalized more than those corresponding to the lower coefficients during the optimization procedure [12]. Hence, the MNM algorithm used in [11] is unable to preserve the clinically important higher wavelet coefficients during joint MECG recovery. The problem gets more pronounced when the number of measurements is less, which results in higher reconstruction error. To address this issue in SMV formulations, methods based on iterative re-weighting were proposed [12,14]. These algorithms received significant attention due to their improved performance over their non-weighted counterparts. The reweighted SMV algorithms can be directly extended for the MMV problems (like joint MECG recovery) by using mixed-norm optimization [13]. A similar idea was used in [15], where a weighting scheme in accordance with the importance of singular values was proposed to enhance the performance of standard nuclear norm minimization. Thus, it can be concluded that the weighting approach allows more flexibility and enables easy incorporation of additional constraints in the joint optimization problems [14]. This motivated us to use a weighting scheme in the traditional MNM-based recovery algorithms. This is expected to further improve their recovery performance, especially at low measurement rates.

In the present study, an improved weighted MNM (WMNM) algorithm is proposed for the joint CS reconstruction of MECG signals by efficiently exploiting the inter-channel correlation. The proposed weighting strategy intends to prioritize the higher amplitude ECG wavelet coefficients whose indices form the row support of jointly sparse MECG signals during the joint CS-based reconstruction. The insignificant lower amplitude coefficients are de-emphasized simultaneously. These coefficients correspond to the indices that are more likely to fall outside the row support of jointly sparse MECG signals, and therefore are expelled from the row support in the final solution. It enhances the sparseness of the solution and reduces the number of measurements required for accurate recovery. The traditional MNM-based algorithms lack this flexibility. Additionally, a pre-defined weighting rule based on the prior knowledge about MECG wavelet representation is explored that exploits prior structural knowledge about the common support of diagnostically relevant MECG wavelet coefficients to determine the weights.

The rest of the paper is organized as follows: the MMV-based CS modeling and the WMNM-based recovery of the MECG signals are discussed in Section 2. Experimental results on different databases and the related discussions, including recovery performance analysis, comparative study, and application related issues, are presented in Section 3. The concluding remarks are given in Section 4.

2. Methods

In standard practice, MECG signals are recorded in a 12-channel format [9]. Out of these 12-channels, there are eight independent channels: I, II, V1, V2, V3, V4, V5, V6; and the remaining four are derived channels: III, aVR, aVL, aVF. We have processed the eight independent channels in this work because the derived channels can be synthesized using the independent limb leads, I and II. Hereafter, MECG will refer to eight channels instead of 12-channels. The MECG signals are jointly encoded using a sensing matrix at the encoder. The resulting compressed measurements are collected at the decoder where all the ECG channels are simultaneously reconstructed with the help of proposed recovery technique. The compressed measurements can be quantized and Huffman encoded to further enhance the compression efficiency of the system. The main contribution of this work focuses on the joint reconstruction algorithm that uses a weighting strategy to emphasize the clinically important wavelet coefficients while exploiting the underlying inter-channel correlations. The aim

Please cite this article as: A. Singh, S. Dandapat, Weighted mixed norm minimization based joint compressed sensing recovery of multi-channel electrocardiogram signals, Computers and Electrical Engineering (2016), http://dx.doi.org/10.1016/j.compeleceng.2016.01.027