EXPLORING THE NON-LOCAL SIMILARITY PRESENT IN VARIATIONAL MODE FUNCTIONS FOR EFFECTIVE ECG DENOISING

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ABSTRACT

ECG is corrupted by various noises and denoising of ECG is central to proper diagnosis of cardiac diseases. The main objective of this work is to exploit the efficacy of non-local means (NLM) for ECG denoising. In the presented work, noisy ECG signal is decomposed into variational mode functions (VMFs) using variational mode decomposition (VMD) technique. The decomposed VMFs represents the different frequency band of the noisy ECG signal. The non-local similarity present in each VMFs were exploited using NLM estimation for effective ECG denoising. The two-stage VMD decomposition and NLM estimation process is performed on different set of VMFs at both stages. The proposed method is tested upon MIT-BIH Arrhythmia database. The denoising performance of existing techniques is compared to proposed method. The computed results shows that the proposed method gives superior denoising performance.

***Index Terms*—** Electrocardiogram, denoising, variational mode decomposition, variational mode function, Non-local means

1. INTRODUCTION

Electrocardiogram (ECG) signal represents the electrical picture of human heart. It consists of important clinical parameters and aids in diagnosis of cardiac diseases [1]. The primary problem associated with ECG recording process is noise contamination. During ECG acquisition process, various noises such as baseline wander (BLW), power-line interference (PLN), motion artifacts (MA), disturbance in recording device, etc affects ECG signal [1, 2]. During ambulatory ECG recording white Gaussian noise (WGN) abducts ECG signal [3]. Denoising becomes key for any further signal processing on ECG signal. These noises affects different frequency band of original ECG signal. BLW noise corrupts the lower frequency band, PLI adds 50/60 Hz line frequency where as MA, device noises, WGN and other burst noises affects the entire frequency range of the ECG signal.

Many ECG denoising techniques can be found in literature [4, 5, 6, 7, 8, 9, 10, 11, 12]. In [13, 12, 5], PLN and BLW affected signal were denoised using empirical mode decomposition (EMD) and discrete wavelet transform (DWT) methods. In [14, 7], denoising of ECG signals affected by MA is performed by wavelet based method. In [4, 6, 9, 10, 3], WGN noise based denoising frameworks were proposed. In [8], nonlinear Bayesian filtering framework is proposed.

Most of the these methods are based on EMD-domain thresholding [5, 9, 13] and wavelet domain filtering [7, 15, 11]. In [4], patch-based non-local means (NLM) technique applied on raw noisy ECG for its denoising is proposed. It's performance is quite competitive with existing state-of-art methods in terms of distortion and mean-square error measurement of denoised output. The major challenge with NLM method is the "rare-patch"effect [4]. The abrupt amplitude and frequency variation around QRS-complex region leads to rare-patch effect, resulting in ineffective QRS-region denoising.

Recently, variational mode decomposition (VMD) [16] has been proposed to decompose the signal into predefined number of narrow-band variational mode functions (VMFs). Each VMFs represents smaller portion of the overall frequency band of the signal. Unlike ECG, these VMFs does not have abrupt amplitude or frequency variation, thus suitable for NLM technique. Motivated by this, a novel two-stage VMD-NLM framework for is proposed effective ECG denoising. The set of VMFs in desired frequency-band are computed from noisy ECG signal for both stages and NLM estimation is performed on selective VMFs. The effective implementation of NLM in VMF denoising results in overcoming the "rare-patch"effect in NLM technique. The simulations are performed on MIT-BIH Arrhythmia database [17]. The proposed method outperforms the existing approaches based on the qualitative and qualitative approaches.

The rest of paper is organized as follow: Section 2 describes the Proposed ECG denoising methodology. Section 3 presents the experimental results and a discussion on the same. Finally, the paper is concluded in Section 4.

2. PROPOSED METHODOLOGY

The overall proposed ECG denoising process is depicted in Figure 1. Firstly, the noisy ECG signal is decomposed into

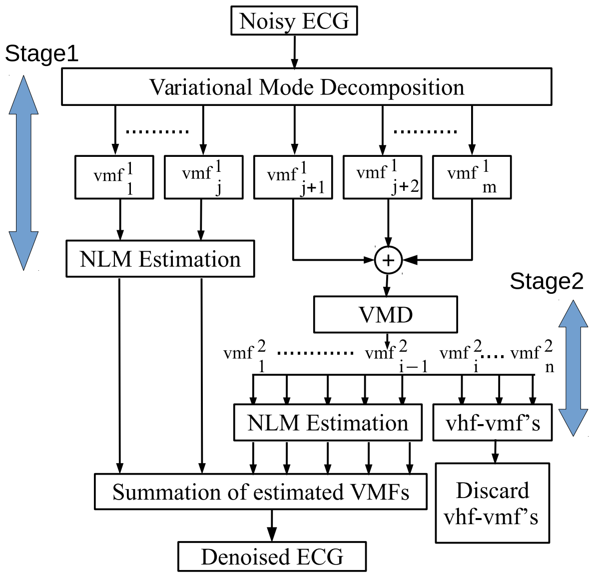

Fig. 1. Proposed method for ECG denoising. Stage-1 and stage-2 processes are marked by vertical arrow.

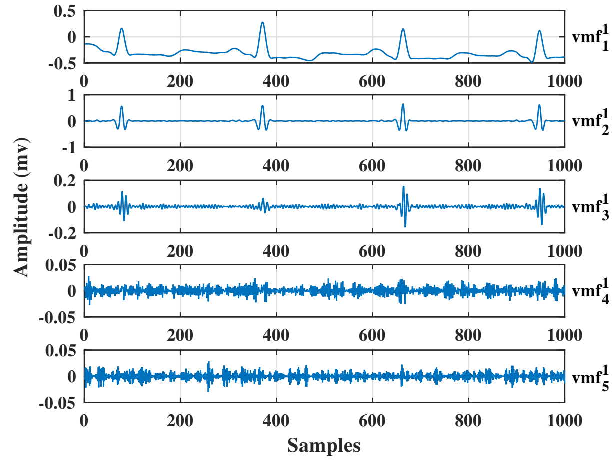

Fig. 2. Stage 1 variational mode functions (VMFs). The modes are arranged from low- to high-frequency band.

m number of narrow-band VMFs (represented as vmf_m^1) at stage-1. These VMFs are arranged from low-frequency to high-frequency band region of the ECG signal. The low-frequency band VMFs (i.e from vmf_1^1 to vmf_j^1) are first processed using NLM-estimation. The rest of stage-1 high-frequency VMFs (vmf_{j+1}^1 to vmd_m^1) are summed together and further decomposed into n VMFs at stage-2. The value of n is kept greater than m to get the fine information residing in high-frequency ECG signal for effective denoising. The selection of VMFs subjected to NLM estimation at both stage is explained in section 2.3. The first $i-1$ VMFs (vmf_1^2 to vmf_{i-1}^2) in stage-2 having non-local similarity and containing fine clinical information are then estimated by NLM technique. The rest of very-high frequency VMFs ($vhf - vmfs$) from vmf_i^2 to vmf_n^2 are mostly high frequency noises. The $vhf - vmfs$ contains very little significant information as they mostly lie outside the typical ECG signal frequency range. The denoised output is achieved by summing the stage-1 and stage-2 NLM estimated VMFs. The VMD decomposition process, NLM estimation technique, and VMFs selection- and denoising-processes are explained as follows:

2.1. Variational Mode Decomposition

Variational mode decomposition (VMD) is a non-recursive, concurrent, signal decomposition method [16]. It looks for the ensemble of modes and their center frequency. The decomposed variational mode function (VMFs) represents the narrow-band frequency region of the input signal. For a given input signal, VMD computes predefined number of variational mode functions, v_k, and their corresponding central frequency, f_k. The mode central frequency (f_k) are sparsity priors and helps in reproduction of input signal. To compute v_k and f_k, the constrained variational problem is solved which is given as:

$$\min_{\{v_k\},\{f_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_k(t) \right] e^{-j f_k t} \right\|_2^2 \right\} \quad (1)$$

such that $\sum_k v_k = x$. k is total number of decomposed modes. The reconstruction constraint is solved with help of Lagrangian multipliers, $\lambda(t)$ and quadratic penalty term. The resultant VMFs computed in frequency domain, $\hat{v}_k$, is as follows:

$$\hat{v}_k^{n+1}(\omega) = \frac{\hat{x}(\omega) - \sum_{i \neq k} \hat{v}_i(\omega) + \frac{\hat{\lambda}(\omega)}{2}}{1 + 2\alpha(\omega - \omega_k)^2} \quad (2)$$

The inverse Fourier transform is used to calculate the corresponding time domain VMFs, v_k. Figure 2 and 3 represents the decomposed VMFs and their corresponding magnitude spectrum for a noisy ECG signal at $k = 5$. The detailed discussion on working of VMD is given in [16].

2.2. NLM estimation process

The NLM technique finds the non-local similarity present in the noisy input signal y for denoising purpose [4]. It is a patch based technique (patch represents group of sample points in the signal) which compares two patches to find non-local similarity. For a given sample p, the denoised estimation $\hat{x}(p)$ is weighted sum of sample values at another point q in the search-neighborhood $Z(p)$

$$\hat{x}(p) = \frac{1}{Y(p)} \sum_{q \epsilon Z(p)} w(p,q) y(q) \quad (3)$$

where $Y(p) = \sum_q w(p,q)$. The weight value ($w(p,q)$) is computed by weighted squared-difference of patches centered

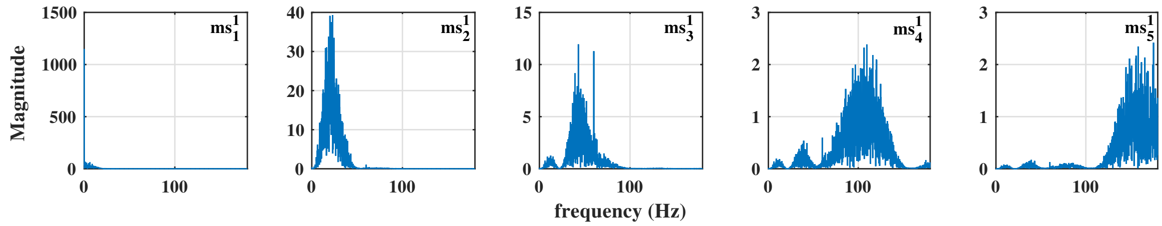

Fig. 3. Magnitude Spectrum of stage 1 VMFs. They are arranged from low- to high-frequency band region (left to right.

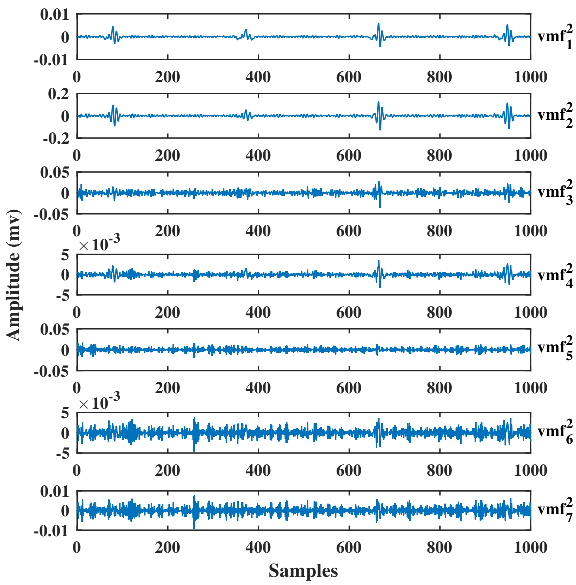

Fig. 4. Stage 2 variational mode functions (VMFs). The modes are arranged from low- to high-frequency band (top to bottom).

at p and q, respectively. It is mathematically represented as:

$$w(p,q) = \exp\left(-\frac{\sum_{\Delta\epsilon\delta}\Big(y(p+\Delta) - y(q+\Delta)\Big)^2}{2L_\delta\tau^2}\right) \quad (4)$$

where τ is bandwidth parameter, δ represents the patch of samples with L_δ sample points. The NLM novelty is that the weight's depends on similarity between patches and not on physical distance between patches.

2.3. VMFs selection, denoising and signal reconstruction

The selection of VMFs at two-stages in the proposed methods is done based on the efficacy of NLM estimation. As pointed out in section 1 that, the NLM denoising technique works effectively by finding the non-local similarity but suffers from the rare-patch problem. The resulting rare-patch effect is due to the fact that, the ECG signal contains abrupt amplitude and frequency variation around the QRS-complex region. This effect results in ineffective denoising of QRS-region. On other hand if properly decomposed, the VMFs can have lesser amplitude and frequency variation as suitable for NLM . Also to compliment NLM efficacy, these VMFs have non-local similarity. Keeping in mind the fact that the very large and small VMD decomposition levels results in under-binning (loss of ECG information) or over-binning (mode duplication) of modes [16], a 5 mode decomposition is performed at stage-1. The stage-1 VMFs ($vmf_m^1 = (vmf_1^1, vmf_2^1.....vmf_5^1)$) and its magnitude spectrum ($ms_m^1 = ms_2^1, ms_2^1...ms_5^1$) are shown in Figure 2 and 3 respectively. It can be observed that, the initial two modes (vmf_1^1 and vmf_2^1) contains lesser amplitude-frequency variation and significant non-local similarity, thus ideal for NLM estimation. The remaining VMFs (vmf_3^1 to vmf_5^1) lie in the high-frequency range and have abrupt amplitude variation. But they contain some significant ECG information and needs further inspection. To do so, these remaining stage-1 VMFs are summed together and subjected further to 7-mode VMD decomposition at stage-2. These VMFs are represented as $vmf_n^2 = (vmf_1^2, vmf_2^2, ...vmf_7^2)$ as shown in Figure 4. The initial 3 VMFs (vmf_1^2 to vmd_3^2) are subjected to NLM estimation as they contain some significant high-frequency-ECG information. The remaining stage-2 VMFs mostly contains high-frequency noises are discarded. The final reconstruction is done by adding the processed VMFs at both stages.

3. EXPERIMENTAL EVALUATION

3.1. Experimental setup

The experimental evaluation is performed on MIT-BIH Arrhythmia database [17]. The records in database are sampled at 360 Hz and at 11 bits resolution. Each record contains 2 leads ECG data, MLII lead and V5 lead. This work uses MLII lead and the record used for comparison are kept similar to ones used in existing discussed techniques [4]. This work uses 10 second raw ECG (3600 samples) data for all simulation purpose. To simulate various noises, white Gaussian noise (WGN) is added to raw signal at different input signal-to-noise ratio (SNR). Also random noise at standard deviation of 0.20 is added to simulate Motion artifact (MA). The performance metrics used for all quantitative result comparison are kept similar to the ones used in [4]: signal-to-noise ra-

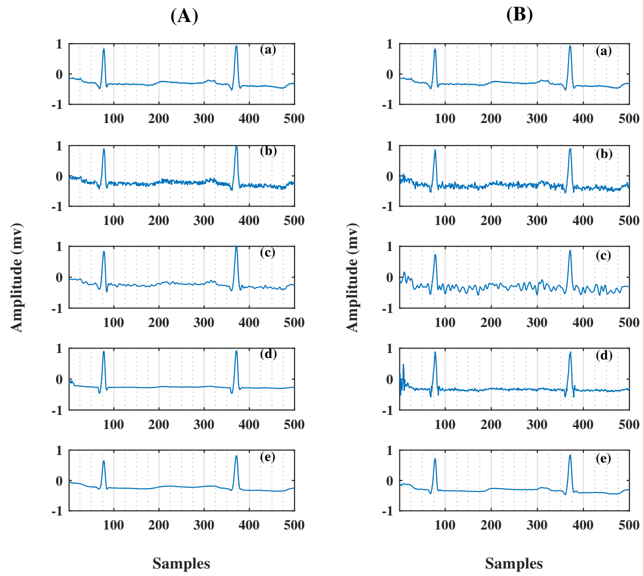

Fig. 5. Denoised EGC signal obtained for: (A) WGN noise and (B) motion artifact (MA). (a) Raw ECG, (b) Noisy ECG, (c) DWT-thresholding (d) NLM method, (e) Proposed method

tio improvement (SNR_{imp}), mean-square error (MSE) and percent-root distortion. These metrics informs about various aspect of denoised signal compared to the raw and noisy ECG signals. The critical NLM parameters are set as: patch size = 12 samples, search-neighborhood size = 50 samples and bandwidth parameter is $\tau = 0.75\sigma$. where σ being the noise standard deviation. The VMD stage-1 decomposition level is set at $m = 5$ and that for stage-2 is $n = 7$.

3.2. Results and Discussion

To establish the efficacy of proposed approach, it has been compared with existing DWT-thresholding [15] and NLM-estimation [4] techniques. Figure 5 shows the qualitative comparison of the proposed method with existing methods for both WGN and MA noises. The morphological structure is effectively retained by proposed method compared to existing one for both noises.

The quantitative comparison results are shown through Figure 6 and Table 1. The results are compared based on performance metrics discussed in subsection 3.1. In Figure 6(a) and (b), the SNR_{imp} for discussed methods are compared for different set of input SNR and test signals respectively. Similar comparison is made based on PRD values in Figure 6 (c) and (d). The MSE values for the compared methods are shown in Table 1 for various test signals. The resultant SNR_{imp} value for proposed method is significantly higher than the existing methods. Also the MSE and PRD values are lower for the proposed work as desired.

These results shows that the proposed denoising method performs better compared to discussed methods both qualitatively and quantitatively. The NLM ill-effect of rare-patch effect has been effectively overcame in this work. It is to note that, NLM algorithm will work efficiently if applied on narrow-band signals with lesser amplitude variation compared to raw ECG with abrupt amplitude variation around QRS-complex region.

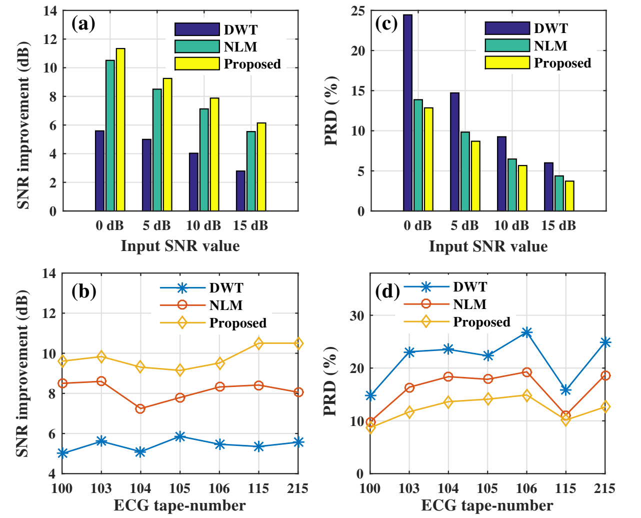

Fig. 6. Comparison of SNR improvement and PRD with varying SNR levels for different explored denoising methods.

Table 1. The MSE values for the explored approaches with respect to all test signals at 5 dB input SNR value.

ECG Signal	DWT-thresholding	NLM	Proposed
100	0.0029	0.0013	0.0009
103	0.0081	0.0041	0.0020
104	0.0074	0.0045	0.0025
105	0.0073	0.0047	0.0027
106	0.0132	0.0068	0.0030
115	0.0080	0.0041	0.0024
215	0.0047	0.0027	0.0023

4. CONCLUSION

In this paper, a two-stage VMD-NLM based ECG denoising techniques has been proposed. The noisy ECG is decomposed into VMFs with exclusive decomposition capability of VMD. The resultant narrow-band VMFs selected at both stages are efficiently processed through NLM technique for effective denoising. The proposed work overcomes the rare-patch effect of NLM technique by proper VMFs selection. The proposed method works effectively on both white Gaussian noise (WGN) and motion artifact (MA), and retains the significant morphological information of ECG. In Future, efforts will be made to incorporate denoising of power-line interference and baseline wander. The results are found to be superior compared to the existing method both qualitatively and quantitatively .

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