Adaptive Modulation Spectral Filtering for Improved Electrocardiogram Quality Enhancement

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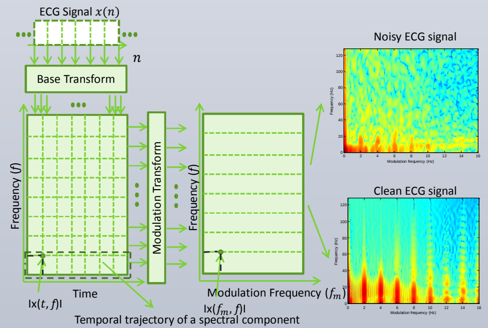
INTRODUCTION

- Advances in portable electrocardiogram (ECG) monitoring devices has allowed for new cardiovascular applications to emerge beyond diagnostics, such as stress detection, sleep disorder characterization, mood recognition, activity surveillance, or fitness monitoring.
- Low-cost ECG devices are prone to artifacts, particularly due to movement, thus hindering heart rate and heart rate variability (HRV) measurement.
- ECG quality enhancement algorithms are drastically needed that can operate under a wide range of noise levels.
- Typically, three main methods have been explored for ECG quality enhancement: (time or frequency-domain) filtering, empirical mode decomposition (EMD), or wavelet shrinkage.
- A new ECG quality enhancement algorithm based on adaptive filtering in the **spectro-temporal domain**, also known as modulation spectral domain, is proposed.

MODULATION SPECTRAL DOMAIN

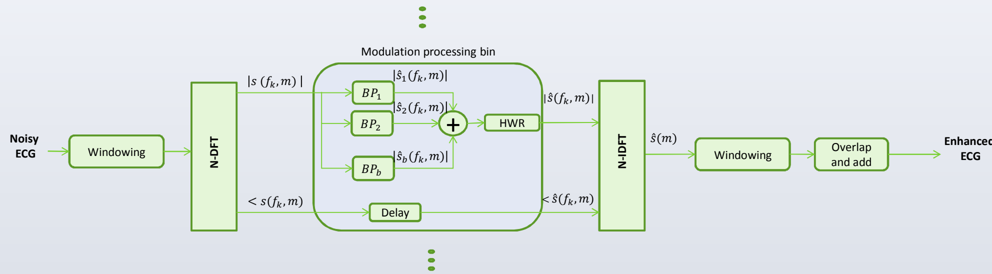
- This signal representation characterizes the rate-of-change of ECG spectral components, which was shown to differ from the rate-of-change of artifactual components.
- This representation accurately separates ECG signal and noise components, thus allowing for adaptive filtering to improve signal quality even in extremely noisy settings.



- The signal is segmented using a 32-point sine window with 75% overlap and transformed to time-frequency domain using a 512-point Fast-Fourier transform (FFT).
- Spectral magnitude components are segmented over time using a 128-point window with 75% overlap. A 512-point FFT across the time axis is performed to result into a final frequency-frequency representation.

PROPOSED MODULATION FILTERING METHOD

- By utilizing invertible transforms to obtain the spectro-temporal signal representation, filtering can be performed in the modulation spectral domain and the enhanced signal can be reconstructed.



- A Fast-Fourier transform is taken where the $|s(f,m)|$ magnitude for each frequency bin (f at m time step) is filtered up to f = 40Hz.
- Each modulation processing bin has a bank of B adaptive linear-phase Finite Impulse Response (FIR) bandpass filters with length 432 to generate $|\hat{s}_b(f,m)|$. Bandpass filters are centred at the main lobe and several of its harmonics.
- After filtering, the $|\hat{s}_b(f,m)|$ are added and half wave rectification (HWR)) is used to compensate for potential negative magnitude spectra that can result from low modulation frequency removal. Moreover, the phase $< s(f,m)$ is delayed by 216 samples resulting in $< \hat{s}(f,m)$.
- Finally, the processed magnitudes and phases from the N bins are transformed via an inverse Fourier transform into $\hat{s}(m)$, followed by windowing and overlap-add to obtain the enhanced ECG signal.

RESULTS

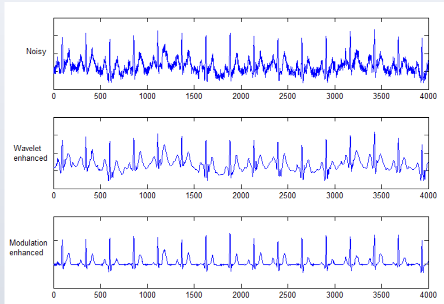
- Synthetic ECG signals with 2-minute duration were generated and then contaminated with real artifacts taken from the MIT-BIH Noise Stres Test database at different SNRs. Heart rate values ranged from 50 to 180 bpm and the low frequency to high frequency ratio was randomly sampled from 0.5 to 8.9.
- Wavelet shrinkage algorithm with soft thresholding and a Daubechies mother with 8 decomposition levels was used as a benchmark ECG enhancement method.

Noisy		Proposed		Benchmark	
Input SNR (dB)	Kurtosis	Post-SNR (dB)	Kurtosis	Post-SNR (dB)	Kurtosis
-10	3.1±0.0	1.4±1.2	6.2±1.5	-2.3±0.1	3.0±0.1
-8	3.4±0.0	2.5±1.3	7.3±1.6	-2.0±0.2	3.5±0.1
-5	4.2±0.2	3.9±1.2	8.6±1.7	-1.2±0.2	4.4±0.3
0	5.6±0.4	5.5±0.9	10.0±1.7	1.2±0.2	5.8±0.6
5	6.3±0.6	6.4±0.7	10.7±1.7	5.0±0.2	6.5±0.8

- Kurtosis was used as one figure of merit, as higher kurtosis values correspond to improved quality (typically correspond to good quality ECGs).
- SNR improvement for noisier signals (SNR=-10, -8, -5, and 0 dB) with the proposed algorithm was 9 dB compared to 4 dB with the benchmark.
- An average kurtosis increase over the noisy signal of 4 was obtained with the proposed algorithm, thus outperforming the increase of 0.1 obtained with the benchmark.

RESULTS (CONTINUED)

Representative plot: ECG signal with 60 bpm and SNR = 0dB before (top) and after wavelet-based enhancement (middle) and the proposed (bottom) modulation filtering scheme.



CONCLUSIONS

- Experimental results show the proposed algorithm outperforming a state-of-the-art wavelet-based enhancement algorithm in terms of signal-to-noise ratio improvement, as well as ECG kurtosis.
- The obtained findings suggest that the proposed technique is well suitable for lower-cost wearable ECG devices that can be greatly contaminated by movement artifacts.
- The proposed algorithm can be used to enhance the quality of wearable ECG monitors even in extreme conditions, thus can play a key role in athletic peak performance training/monitoring.
- Since ECG components around $f_m = 0Hz$ were severely affected by noise, they are discarded completely at the cost of imperfect reconstruction of the ECG signal. This can lead to issues with diagnostics where perfect QRS complexes are needed.
- To measure HR/HRV metrics, however, the removal of modulation frequencies around $f_m = 0Hz$ did not show to be a severe perfomance degrading factor.
- Alternate strategies on how to handle the lowpass stationary modulation components are still needed for clinical diagnostic applications.

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