Exploiting Ambient Light Interference to Detect Signal Integrity in Photoplethysmographic Recordings

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Abstract

Photoplethysmography (PPG) is widely used in wearable devices for monitoring cardiovascular health, but its signal quality can be severely affected by ambient light interference and suboptimal sensor-skin contact. In this study, we propose the Contact Quality Index (CQI), a novel metric based on spectral analysis of the ambient light channel, designed to quantify signal integrity in real time. Data were collected using a wrist band which provided an ambient light channel synchronized with three PPG channels. The CQI was computed from the Power Spectral Density (PSD) of the ambient light signal, capturing deviations that correlate with light-induced artifacts and poor contact. Validation experiments demonstrated a strong association between the CQI and signal quality. Specifically, higher PSD values of the ambient light signal were indicative of unstable sensor contact and significant ambient light perfusion. In contrast, properly positioned sensors showed lower PSD values, reflecting stable contact and minimal external light disturbance. Compared to traditional signal quality indices, the CQI provides a computationally efficient, interpretable, and morphology-independent metric that is particularly suited for integration into wearable health monitoring systems. The proposed approach enables detection and rejection of corrupted segments, enhancing robust real-time monitoring.

1. Introduction

Photoplethysmography (PPG) is widely used for monitoring cardiovascular parameters such as HR, HRV, and SpO2 [1, 2], thanks to its non-invasive nature and easy integration into wearables [3]. It underpins modern health monitoring technologies and is applied in fitness tracking, remote patient monitoring, and early detection of cardiovascular diseases [4]. However, PPG reliability is often challenged by noise, notably ambient light interference [5].

PPG sensors detect light intensity reflected or transmitted through the skin [6], but external sources like sunlight and artificial lighting introduce noise, causing amplitude fluctuations and waveform distortions that hinder parameter extraction [7]. These effects are more severe in uncontrolled environments with dynamic lighting [7].

To mitigate ambient light interference, hardware and software strategies have been proposed [8, 9]. Yet, their effectiveness is limited in wearables due to constraints in real-time processing, power consumption, and adaptability [10], highlighting the need for efficient methods.

This work introduces the Contact Quality Index (CQI), a spectral analysis-based metric for assessing PPG signal quality. Derived from the Power Spectral Density (PSD), the CQI estimates noise levels and identifies segments affected by ambient light interference—often linked to poor sensor-skin contact.

2. Materials and Methods

Ambient light signals were acquired using the Polar Verity Sense device (Polar Electro Oy, Finland), a wearable optical sensor providing three PPG channels and a dedicated ambient light channel. This configuration enables synchronized signal acquisition at a fixed sampling rate of 55 Hz. The dataset comprised recordings from 50 patients in which 60% were women, 10% led active lifestyles and 60% were under cardiovascular medications like beta-blockers or statins. Participants followed their daily routines while wearing the device.

The ambient light signal was segmented into fixed-length windows of 5 seconds to facilitate time-resolved

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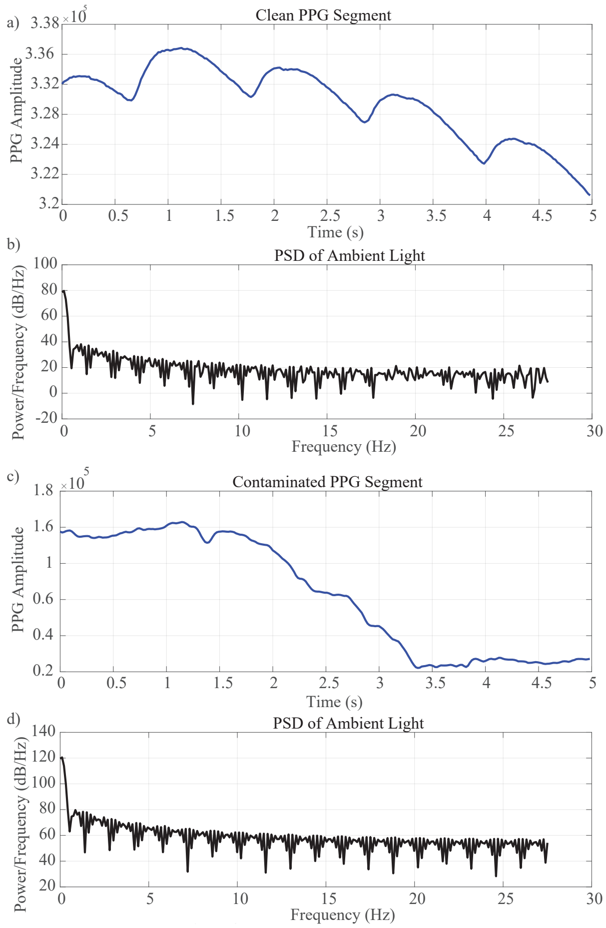

Figure 1: Examples of ambient light contamination in PPG signals. (a) Proper sensor placement yields a clean PPG signal; (b) its corresponding power spectral density shows low noise levels. (c) Improper placement causes ambient light contamination, resulting in a corrupted PPG signal; (d) the PSD reflects increased overall energy due to noise.

analysis of environmental interference, as ambient light conditions can change rapidly over short time intervals. Each segment was processed independently to detect transient events, such as sensor displacement or sudden exposure to external light sources. For each 5-second window, the PSD of the ambient light signal was estimated using Welch's method [11]. A 50% overlap between subsegments was applied to ensure temporal continuity and enhance the statistical reliability of the PSD estimate. To mitigate spectral leakage and improve frequency resolution, a Hamming window was applied to each subsegment before performing the Fourier Transform. An FFT length of 2048 points was selected to achieve fine-grained identification of spectral components.

The PSD will be used to highlight distinct patterns that correspond to varying sensor contact conditions, as illus-

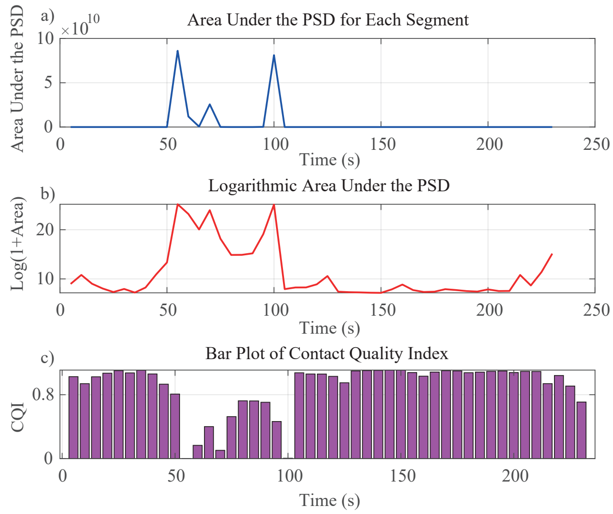

Figure 2: Workflow for CQI computation. a) Raw PSD area per segment, capturing total spectral power. b) Logarithmically transformed PSD values to enhance visibility of variations. c) Normalized and inverted CQI, providing a continuous indicator of signal contamination.

trated in the example of Figure 1. When the sensor is properly affixed to the skin, the PSD exhibited reduced values. This pattern would suggest minimal interference from ambient light and stable contact, allowing for reliable extraction of physiological information.

To objectively capture and quantify these variations in signal quality, the Contact Quality Index (CQI) is proposed, with a computation pipeline as shown in Figure 2, which consists of three key steps. First, the PSD area is calculated for each 5-second segment via numerical integration using a trapezoidal method with unit spacing, thus capturing the total spectral energy. Given the wide dynamic range of the PSD values, a logarithmic transformation is applied to compress large variations and enhance interpretability. Finally, the transformed values are normalized to a 0-to-1 range based on the minimum and maximum values observed across all the patient's recordings, and then inverted, so that higher CQI values correspond to better sensor-skin contact and reduced ambient light contamination.

To further validate the effectiveness of the CQI as a proxy for signal fidelity, signal quality was assessed on 345,600 segments. For each segment, the Signal-to-Noise Ratio was computed using a MATLAB function, considering as signal the standard frequency components of the PPG and as noise the remaining spectral content, along with standard SQI indices—skewness, kurtosis, and entropy [12]—and the Contact Quality Index. These metrics were then averaged across all segments. Pearson's correlation coefficient (r) and the corresponding p-value between the CQI, SNR, and SQIs were calculated.

3. Results

Based on CQI and SNR values, two distinct quality groups were identified: segments with signal-to-noise ratio (SNR) above 20 dB and CQI values above 0.8 were labeled as having stable contact and minimal artifacts, while segments with SNR below 18 dB and CQI below 0.4 were considered affected by light contamination and unstable sensor contact.

According to this classification, approximately 80% of the segments (276,480) belonged to the stable contact and minimal artifacts group, with an average SNR of 28.03 dB and an average CQI of 0.8. The remaining 20% (69,120 segments) were classified as unstable contact and high artifacts group, showing an average SNR of 14.5 dB and an average CQI of 0.3.

High CQI segments showed lower skewness variability (0.007 ± 0.669) and lower kurtosis (2.392 ± 1.455) compared to low CQI segments (0.173 ± 0.485 and 3.200 ± 2.358, respectively). Entropy was slightly lower in high-quality segments (5.239 ± 0.219) than in poor-quality ones (5.870 ± 0.781).

A significant positive linear correlation was observed between CQI and SNR ($r = 0.72$, $p < 0.001$). Moreover, CQI negatively correlated with skewness ($r = -0.65$, $p < 0.001$), kurtosis ($r = -0.58$, $p < 0.001$), and entropy ($r = -0.62$, $p < 0.01$).

4. Discussion

The CQI demonstrated a clear inverse relationship with ambient light noise: it remained high during stable sensor placement and low environmental noise, and dropped notably in the presence of poor contact or increased light exposure, effectively capturing signal degradation.

High-CQI segments exhibited more symmetric and less peaked signal distributions—evidenced by lower skewness variability, kurtosis, and entropy—reflecting a more regular and stable signal structure. The strong positive correlation between CQI and SNR, along with negative correlations with skewness, kurtosis, and entropy, further supports CQI's validity as a reliable composite metric for assessing PPG signal quality.

Unlike traditional SQIs that rely on waveform morphology [13] or spectral analysis of physiological signal and noise (SNR) [14], CQI specifically targets spectral features of ambient light interference, detecting contamination even without obvious morphological changes. As shown in Figure 3, CQI reliably differentiates high- and low-quality segments, enabling real-time quality feedback. This method addresses a critical need in wearable health monitoring: reliably detecting environmental artifacts that

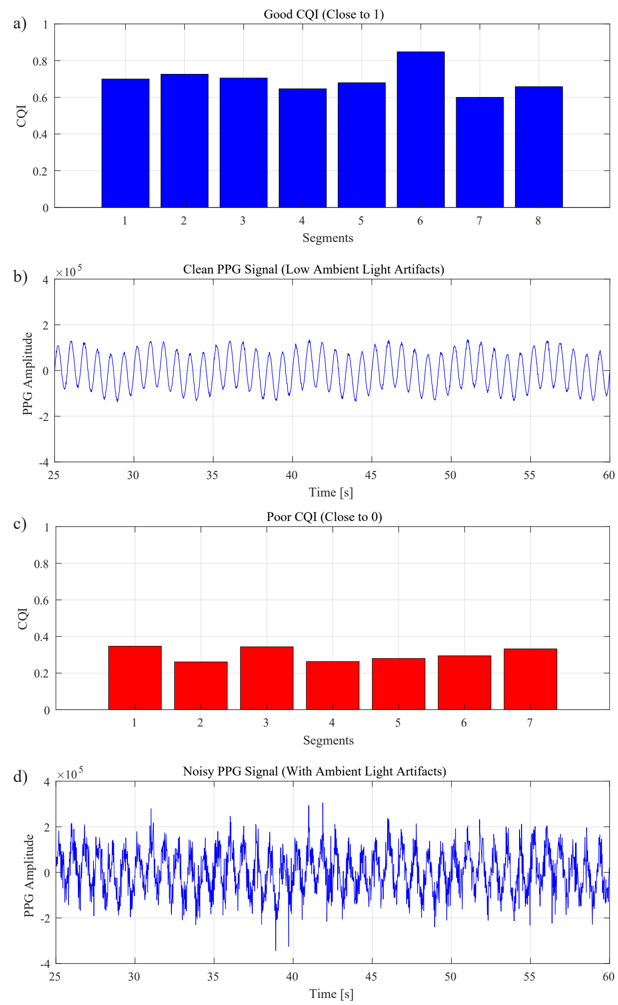

Figure 3: Demonstration of CQI performance under environmental artifacts. Panels (a) and (b) illustrate that high CQI values (close to 1) correspond to clean PPG signals with negligible artifacts, whereas panels (c) and (d) show that low CQI values (close to 0) are associated with noisy PPG signals affected by ambient light interference.

degrade signal quality, while operating with low computational cost and without the need for training data.

Furthermore, machine learning-based classifiers have also been explored for quality assessment; however, they often require large annotated datasets and involve opaque decision-making processes [13]. By contrast, CQI is transparent, lightweight, and explainable—making it well-suited for deployment in resource-constrained systems such as fitness trackers and clinical wearables. Its normalized scale from 0 to 1 allows for easily configurable thresholds based on application requirements.

Moreover, the observed correlation between CQI and other SQIs [12] indicates that it can be seamlessly incorporated into existing quality assessment frameworks as a complementary feature, providing a more comprehensive evaluation that accounts for both morphological signal integrity and environmental interference.

As a future direction, the CQI could be integrated into adaptive preprocessing pipelines to automatically flag or discard low-quality segments before more computationally expensive signal processing steps. This would further enhance the robustness and energy efficiency of wearable monitoring systems.

5. Conclusions

The CQI provides a valuable and interpretable tool for assessing the presence of ambient light artifacts in PPG signal acquisition, effectively accounting for both sensor-skin contact and environmental light interference. However, it is important to note that while the CQI can indicate the absence of external light contamination and suggest good sensor placement, it does not fully capture all potential factors influencing PPG signal quality. Specifically, mechanical movement, which can introduce significant artifacts, is not addressed by the CQI. For instance, even in the absence of ambient light, moving the PPG sensor could still degrade signal quality, resulting in poor signal integrity even when the CQI is high.

This highlights the need for a more comprehensive approach that considers both light contamination and mechanical disturbances. A simple yet effective direction would be to jointly analyze the ambient light channel together with accelerometer data, allowing the estimation of both types of disturbances. Future work will therefore focus on refining the CQI's implementation to incorporate these additional modalities, and on exploring its integration into preprocessing pipelines for adaptive filtering, artifact rejection, and overall signal validation.

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