Signal to Noise Ratio and Current Consumption in LED-LED Photoplethysmography

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Abstract. The signal-to-noise ratio (SNR) and the current consumption of a photoplethysmography (PPG) system based on a LED-LED configuration were estimated. The emitting LED was powered in switched mode using frequencies between 100 Hz and 400 Hz and duty cycles (*D*) between 5% and 30%. The signal from the detector LED was analog conditioned using synchronous demodulation implemented with a zero-order hold circuit that worked at the same frequencies and *D*. An important change in the SNR was observed when the switching frequency and *D* varied. This change was mainly due to the change in the amplitude of the PPG signal because of the changes in the light emitted by the emitting LED, and also by the changes in the frequency response of the synchronous demodulator. Regarding current consumption, the greatest contribution came from the conditioning circuit of the detector LED, since the maximum current consumed by the emitting LED was 51 μA. At 100 Hz and $D = 5\%$, a SNR of 67 dB and current consumption of 2.71 mA were obtained. With the system used in this study, no tradeoff between the SNR and power consumption was observed when the frequency and *D* were changed.

Keywords: LED-LED PPG · Photoplethysmography · Synchronous demodulation

1 Introduction

Photoplethysmography (PPG) is a noninvasive technique used to measure blood volume changes using optical principles [1]. A typical PPG module consists of a light-emitting diode (LED) that illuminates the tissue and a photodiode (PD) that receives small fluctuations of the receiving light due to pulsation of the blood vessels [2]. The demand for wearable technologies calls for autonomous systems, but in such technologies, the quality of the signal is compromised when using low-power devices [3]. Some approaches have been proposed in PPG systems to tackle this. The most common is based on powering the emitting LED using a pulse current (switched-mode power supply) [4], without degrading the radiated power. However, there is a tradeoff between the power consumption and the signal-to-noise ratio (SNR) [5] in a LED-PD configuration.

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With the implementation of PPG modules, favorable results have been obtained with the use of LEDs at near-infrared (NIR) wavelengths and a photodiode, which were integrated into a wristband, allowing direct contact with the skin of the user [6]. In 2003, it was demonstrated that a reflective PPG sensor composed of twelve silicon chips and two pairs of red and infrared LEDs, placed in a ring configuration, increased the battery longevity by using a wide detection area, and limiting the measurement to the forehead region [7]. However, this proposal involves high cost and an increase in size, compromising the form factor of a wearable system. Another complementary study proposed the use of organic light emitting diodes (OLEDs) and an organic photodiode (OPD) to obtain the PPG signal. It was demonstrated that the reflectance-based photoplethysmograph worked successfully with a power consumption of 8 μW, but with a SNR of 18 dB [8].

So far, most of the proposals that seek to reduce power consumption without degrading PPG signal quality are focused on systems based on LED-PD configuration. Some researchers have demonstrated the use of standard LEDs as photodetectors taking advantage of the electroluminescence properties of the LEDs [9]. In such conditions, LEDs can operate in photoconductive mode (output current in presence of light) and photovoltaic mode (output voltage in presence of light) [10]. So, LED-LED PPG can be used to detect, at least, the heart rate [11], but can be extended for the determination of oxygen saturation [12], Pulse Wave Velocity (PWV) [13], and glucose concentration [14].

Unlike previously proposed works in which the power consumption of PPG modules based on LED-PD configuration was studied, in this work, the estimation of the SNR and the current consumption is performed in a LED-LED PPG system. The tradeoff between the SNR and the current consumption is experimentally assessed. For this, the emitting LED was powered in switched mode, and that switching was used as a reference signal in a synchronous demodulator to condition the signal of the detector LED.

2 Materials and Methods

2.1 The LED-LED PPG System

Figure 1 shows the electronic circuit of the LED-LED PPG system. The emitting LED (LED_E) worked at 940 nm. It was supplied in a switched mode by controlling a dual analog SPDT switch (ADG436, Analog Devices) using an arbitrary function generator (AFG202, Tektronix); the quiescent current of the ADG436 was about 50 μA. The output of the function generator was configured to generate a pulse signal with $T_{ON} < T_{OFF}$, so the duty cycle [$D = T_{ON}/(T_{ON} + T_{OFF})$] was lower than 50%. The current of the detector LED (LED_D) circulated through R_D to achieve a voltage proportional to the detected light. The operational amplifier OA1 was configured as a voltage follower to adapt impedances between the LED_D and the demodulator. A zero-order hold circuit using switched capacitors was used as a synchronous demodulator. This stage was controlled by the same pulse signal used to power the emitting LED. That is, during T_{ON}, the capacitor C_S was charged to the output voltage of OA1; during T_{OFF} the voltage stored in C_S was transferred to C_H. The zero-order hold has a frequency response defined by

[15]:

$$H_0(f) = T_{\mathrm{OFF}} \frac{\sin \pi f T_{\mathrm{OFF}}}{\pi f T_{\mathrm{OFF}}} e^{-j\pi f T_{\mathrm{OFF}}} \tag{1}$$

where f is the frequency of the output signal of the arbitrary function generator.

According to the frequency response of the zero-order hold, the Noise Equivalent Bandwidth (NEB) is defined by [16]:

$$NEB = \frac{1}{T_{\mathrm{OFF}}} \tag{2}$$

So, as D decreases, NEB decreases, lowering the noise contribution. Even so, a pass-band filter (0.5 Hz–10 Hz) was connected to the output of the demodulator in order to adapt the noise bandwidth to the PPG signal bandwidth (around 10 Hz) and to suppress the output zero errors from the previous stages. Finally, OA2 implemented with a non-inverting configuration amplified the demodulated signal ($G = 34$), and the output low-pass filter ($f_C = 10$ Hz) reduced the noise contribution coming from the OA2 and the remanent power line interference. OA1 and OA2 were implemented using a general-purpose amplifier TL084, from Texas Instruments, with an input noise voltage of 18 nV/$\sqrt{}$Hz, and a quiescent current of 960 μA (typ).

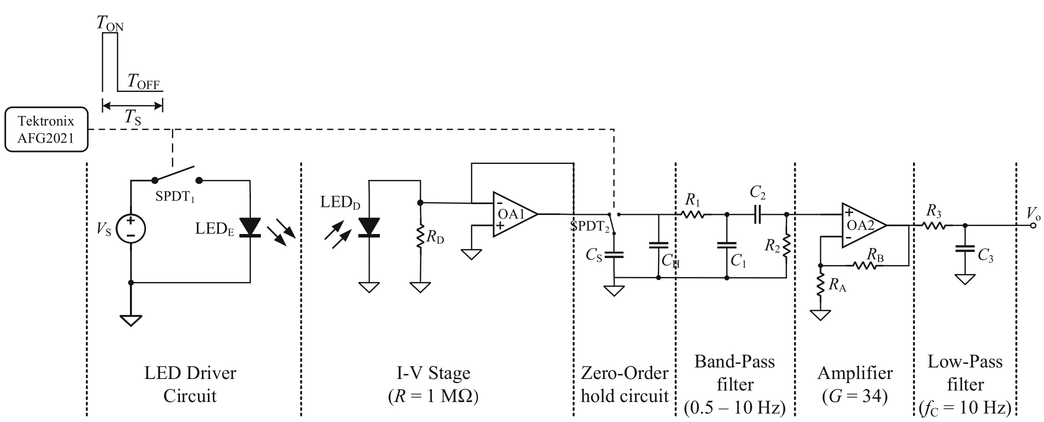

Fig. 1. Schematic of the LED-LED PPG system.

2.2 Signal-to-Noise Ratio and Current Consumption

Figure 2 depicts the measurement setup used to estimate the root-mean-square (rms) value of the noise voltage (E_n) of the circuit used to condition the signal of the detecting LED, and the current consumption of the overall PPG system. In both tests, the output of the generator was configured to generate a pulse signal. The duty cycle was changed between 5% and 30% in steps of 5%, and the frequency was varied between 100 Hz and 400 Hz in steps of 100 Hz. This range of frequency was used because LED switching in most pulse oximeters worked at frequencies around 480 Hz [17], so we wanted to assess the performance of the system at lower frequencies. The conditioning circuit was supplied at ±10 V. A 6 ½ digits DMM 34461A (Keysight) was used to measure E_n (Fig. 2a). It was configured to estimate 1000 samples of DC voltage at 1 PLC (Power Line Cycle). As the electronic noise had a gaussian distribution with a mean value near to 0, the standard deviation equals E_n [18]. So, the following equation was used to estimate the SNR [19]:

$$\mathrm{SNR(dB)} = 20\,\lg\frac{S_{pp}}{N_{pp}} \tag{3}$$

where S_{pp} is the peak-to-peak amplitude of the PPG signal, and N_{pp} is the peak-to-peak noise voltage defined by:

$$N_{pp} = 2\mathrm{CF}E_n \tag{4}$$

where CF is the crest factor (=3 for a probability of 0.37%) [18].

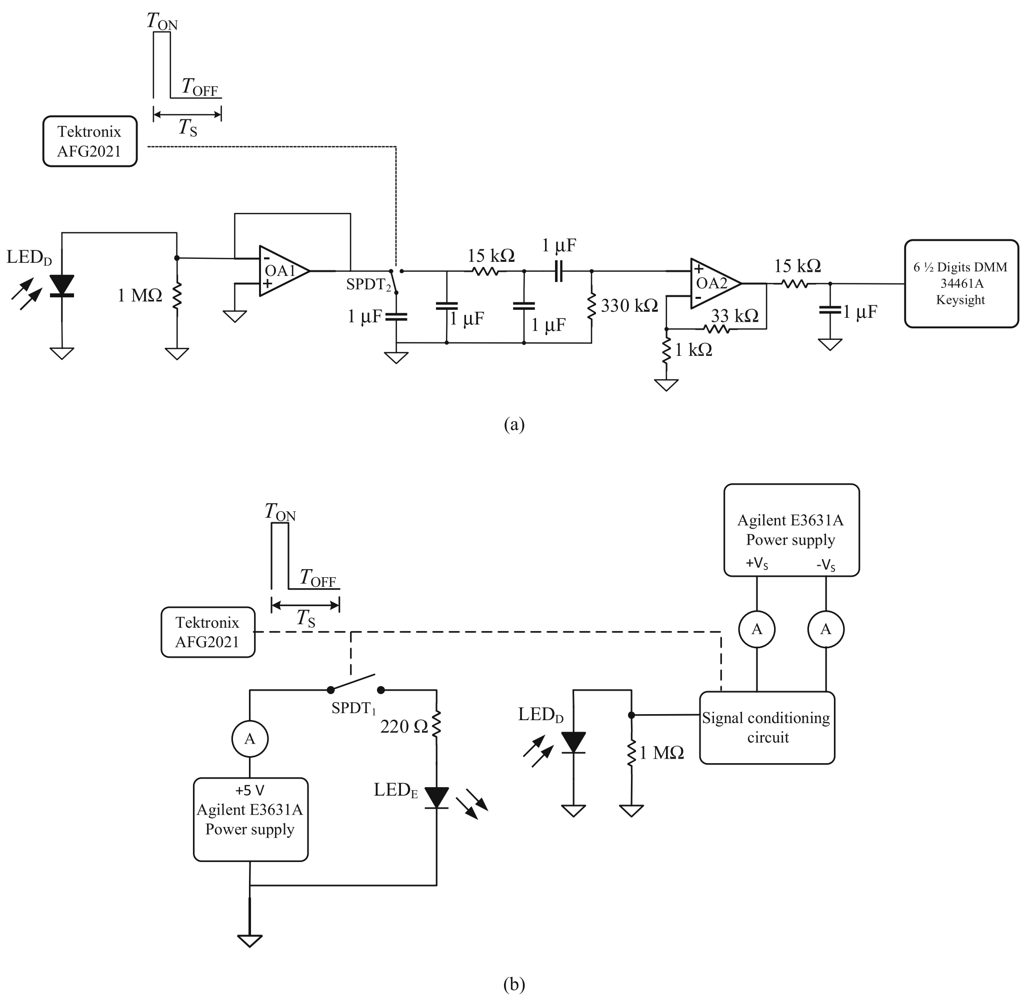

Fig. 2. Experimental setup used to estimate a) spectral density of the noise voltage of the conditioning circuit, b) the current consumption of the overall PPG system.

The current consumption was estimated by measuring the output current from each output of the Power Supply (Fig. 2b). For this, a 6½ digits DMM 34461A (Keysight) was configured as a DC ammeter. The total current consumption (I_{TOT}) was calculated by adding the current consumed by the LED_E (I_{LED}) and the current consumed by the conditioning circuit of the LED_D (I_{CIR}).

To test the system, the PPG was detected on a healthy volunteer sitting at rest (one of the authors) for 10 s in the index finger of the right hand. LED_E was placed at the anterior size of the finger and LED_D was placed at the posterior size, so the transmission of light was detected. All the tests were performed on the same volunteer.

3 Results

Figure 3 shows the PPG signals obtained by the LED-LED system shown in Fig. 1 when the circuit worked at different duty cycles and at frequencies of 100 Hz and 300 Hz (best and worst case, respectively). Firstly, it can be seen how the PPG amplitude varied for different duty cycles when working at one frequency. In the case of $f = 100$ Hz, the highest amplitude was obtained for $D = 5\%$, while for $f = 300$ Hz, the highest amplitude was obtained for $D = 30\%$. This is due, on the one hand, to the fact that at the lower frequency ($f = 100$ Hz, $T_{ON} = 0.5$ ms, $D = 5\%$) the emitting LED is ON for a longer period of time compared to the higher frequency ($f = 300$ Hz, T_{ON} 0.16 ms, $D = 5\%$), which causes more light to pass through the tissue. On the other hand, for a low D, T_{OFF} is larger, which implies, according to (1), a greater attenuation by the low-pass response (defined by $1/T_{OFF}$) of the zero-order hold circuit.

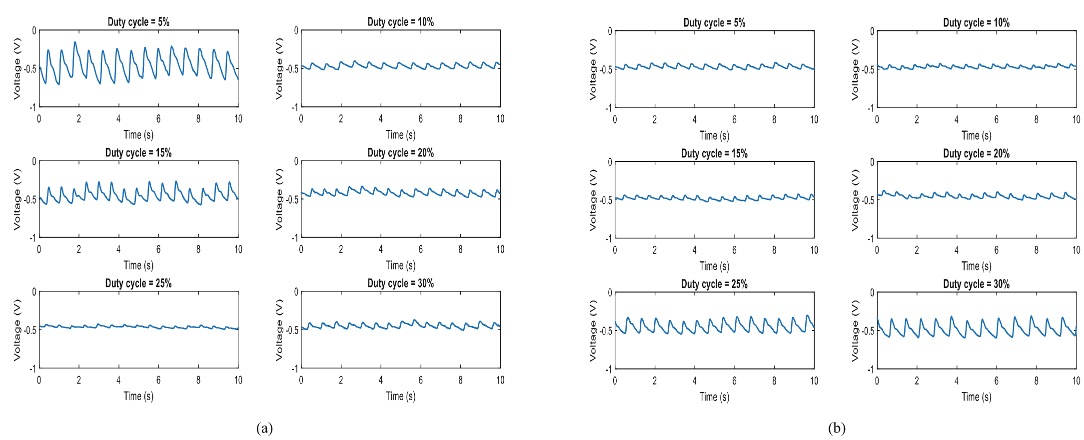

Fig. 3. PPG signals obtained at different duty cycles when the system worked at: a) $f = 100$ Hz, b) $f = 300$ Hz.

The change in frequency and duty cycle also had an impact on the SNR of the PPG signal. Table 1 shows the value of E_n and S_{pp} for different frequencies and duty cycles. Since the noise bandwidth of the circuit in Fig. 1 is defined by the passive filters, changes in frequency and duty cycles have little effect on E_n, but they did have a large effect on S_{pp}, causing the SNR to change significantly for different f and D values. Table 2 shows that the best (67 dB) and worst case (43 dB) were obtained at 100 Hz for $D = 5\%$ and

$D = 25\%$, respectively. However, with the SNR values obtained in all the tests, it can be said that for any of the frequencies used working at different duty cycles, the SNR would allow estimating the heart rate in a simple way. However, to extract parameters such as the perfusion index or respiration, it would be convenient to work at 100 Hz and $D = 5\%$.

Table 1. Root-mean-square value of the noise voltage and the peak-to-peak amplitude of the PPG at different duty cycles and frequencies.

	Frequency (Hz)							
	E_n(rms) (μV)				S_{pp} (mV)			
D (%)	100	200	300	400	100	200	300	400
5	29	39	37	29	371	401	77	224
10	37	41	34	38	82	178	47	388
15	39	38	50	44	239	402	49	140
20	40	43	42	43	89	118	54	94
25	39	51	33	40	35	113	174	107
30	44	48	32	33	84	109	244	256

Table 2. SNR of the PPG signal at different duty cycles and frequencies.

SNR (dB)				
	Frequency (Hz)			
D (%)	100	200	300	400
5	**67**	65	51	62
10	51	57	47	65
15	60	65	44	54
20	51	53	47	51
25	**43**	51	59	53
30	50	52	62	62

Table 3 shows the current consumption of the entire LED-LED system for different frequencies and duty cycles. For this, the consumption of the emitting LED and the consumption of the conditioning circuit were considered. It is known that, for low values of D, the emitting LED draws less current at the expense of lower intensity of emitted light. For example, working at 400 Hz, $D = 30\%$ (worst case) the emitting LED consumed 51 μA, while, for 100 Hz, $D = 5\%$ (best case) the LED consumed 9 μA. In the case of the conditioning circuit, the effect is less prominent since the entire circuit was supplied with a DC voltage. Therefore, the consumption of the entire circuit was mostly due to the op-amps (OA1, OA2) and the SPDT. Hence, the consumption of the entire system barely changed for the different values of f and D. In that sense, for portable applications, the system must be implemented using low-power components, although this would degrade the SNR. To tackle this, it would be convenient to work at $f = 100$ Hz, $D = 5\%$ (Table 2).

Table 3. Current consumption of the LED-LED PPG system at different duty cycles and frequencies

I_{TOT} (mA)				
D (%)	100 Hz	200 Hz	300 Hz	400 Hz
5	2.71	2.72	2.72	2.73
10	2.72	2.73	2.73	2.74
15	2.73	2.74	2.74	2.75
20	2.74	2.75	2.75	2.76
25	2.75	2.75	2.76	2.77
30	2.76	2.76	2.77	2.78

4 Conclusions

In this work, an analog system was used to detect PPG through an LED-LED configuration, that is, using an emitting LED and a detector LED. The advantage of this type of configuration is that an LED only detects wavelengths very close to those it emits, which makes it very selective. The emitting LED was powered in switched mode at different frequencies and duty cycles. Since the detected signal was amplitude-modulated by the changes in arterial volume, a zero-order hold circuit was used as a synchronous demodulator. The operating frequency and duty cycles affected both the SNR of the PPG and the current drawn by the circuit. In the case of the SNR, the change was mainly due to the changes in the amplitude of the PPG signal. This was produced by the changes in the light intensity of the emitting LED and the attenuation of the zero-order hold circuit at different values of D. In portable applications, it would be desirable to power the emitting LED with low frequencies and reduced duty cycles. This combination also achieved a high SNR. For example, for $f = 100$ Hz and $D = 5\%$, an SNR of 67 dB was obtained, and current consumption of 2.71 mA. The greatest contribution of this current came from the signal conditioning circuit of the detector LED, so it is convenient to implement it with low-consumption devices, although this would compromise the SNR. With the system used in this study, no tradeoff between the SNR and power consumption was observed when the frequency and D were changed.

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