“Every photon counts”

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An increasing number of consumer devices are incorporating more advanced biometric monitoring capabilities. What started out with fitness bands worked its way to smart watches, rings, patches, and earbuds.

The technology behind heart rate sensors is called photoplethysmography (PPG). PPG is an optical measurement technique used to detect blood volume changes in living tissues. A PPG sensor requires few optoelectronics components: a light source, typically a light-emitting-diode (LED), a photodetector (PD) to track the variation in detected light intensity due to the blood volume change and an analog front-end (AFE) circuit for signal conditioning and processing. A high fidelity PPG signal can be used to measure important parameters linked to the cardiovascular system, including the heart rate variability, the oxygen saturation, the breathing rate and the blood pressure [1]. Please refer to our application note *“Why the PPG signal fidelity is crucial in vitals extraction?”* for further details.

A PPG signal is obtained by shining light from an LED, typically in the visible or near-infrared range, into human tissue, e.g. finger, wrist, forehead, or the ear. A photodetector detects the light transmitted through (*Transmissive* PPG) or reflected (*Reflective* PPG) from the tissue and transforms it into a photocurrent. The detected signal consists of two separate components, as shown in Figure 1: a large DC (quasi-static) component corresponding to the light diffusion through tissues and non-pulsatile blood layers, and a small AC (pulsatile) part resulting from the diffusion through the arterial blood. The AC component is only a very small fraction (typically 0.1% to 10%) of the DC portion. Actual values for the two components mostly depend on the body location, LED wavelength, and the skin tone [1]. The AC/DC ratio is known as the perfusion-index (PI) and represents one of the practical limits of any PPG system. It is the AC component that carries most of the biomedical information. Low PI values leads to reduced signal fidelity, complicated signal processing schemes and inevitably larger power consumption.

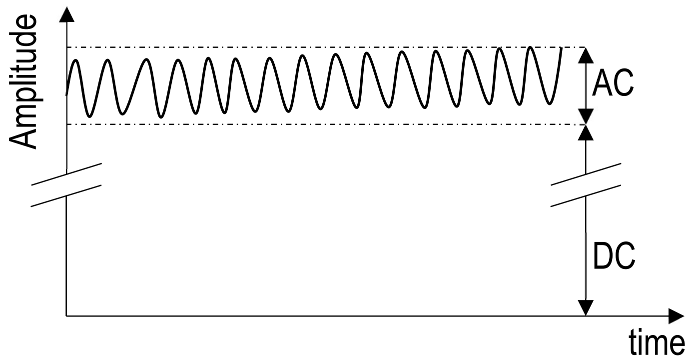

Figure 1: A PPG signal, with the DC and the AC components

Most PPG sensors used to date are based on discrete components, which generally results in larger PPG modules. The discrete elements include photosensitive device (usually a PIN diode), an analog front end (AFE) and an analog-to-digital-converter (ADC). They are often designed to cope with the worst-case PI which results in needing an amplifier chain capable of very high dynamic range conditions and high ADC resolutions (greater than 15 bits) [2]. The use of discrete photodiodes causes them to exhibit a fairly high noise floor, mainly as a result of the photodiode’s high parasitic capacitance [3]. This increases the minimum LED current needed to achieve a specific PPG signal-to-noise ratio (SNR), which ultimately makes for very high PPG module power consumption (requiring large batteries and limiting useful one-charge wear life).

The SNR of the PPG signal is defined as the SNR of the AC component and is denoted SNR_{AC}. The SNR of the total signal is denoted SNR_{DC}. The latter represents the SNR, i.e. the dynamic range, that the PPG readout chain must cope with to ensure the required SNR_{AC}. The SNR_{DC} is usually set upfront larger than 90 dB in order to cope with the worst case PI values [1], at still reasonably large SNR_{AC}. SNR_{AC} and SNR_{DC} terms are linked by the following formula

$$SNR_{AC} = SNR_{DC} + 20\log(PI).$$

The SNR_{DC} can be expressed by the following formula

$$SNR_{DC} = 10\log\left(\frac{N^2}{N+\sigma^2}\right).$$

The first noise source corrupting the signal is the photon shot noise (N). The shot noise variance corresponds to the mean number of integrated photons. The second noise source (σ) is the readout noise, which is independent of the input signal. This noise is also called “read noise” and includes the total noise which the readout circuitry generates. This includes the thermal, flicker and the quantization noise of the ADC. Please refer to [3] for more details.

When the shot noise dominates over the read noise, the SNR_{DC} can be related to the number of photons, N_{min}, to be integrated to reach the SNR_{DC} as follows

$$SNR_{DC} = 10\log(N_{min}).$$

Figure 2 shows, for the reference PI value equal to 1%, how the SNR_{AC} varies versus the equivalent photogenerated current. Two readout circuits are considered: a shot noise limited one and another with a non-negligible read noise. Notice that the shot noise limited readout chain also generates some read noise, but eventually this value is so low that, even under low lightning conditions (a small photogenerated current), we can consider it negligible with respect to the shot noise.

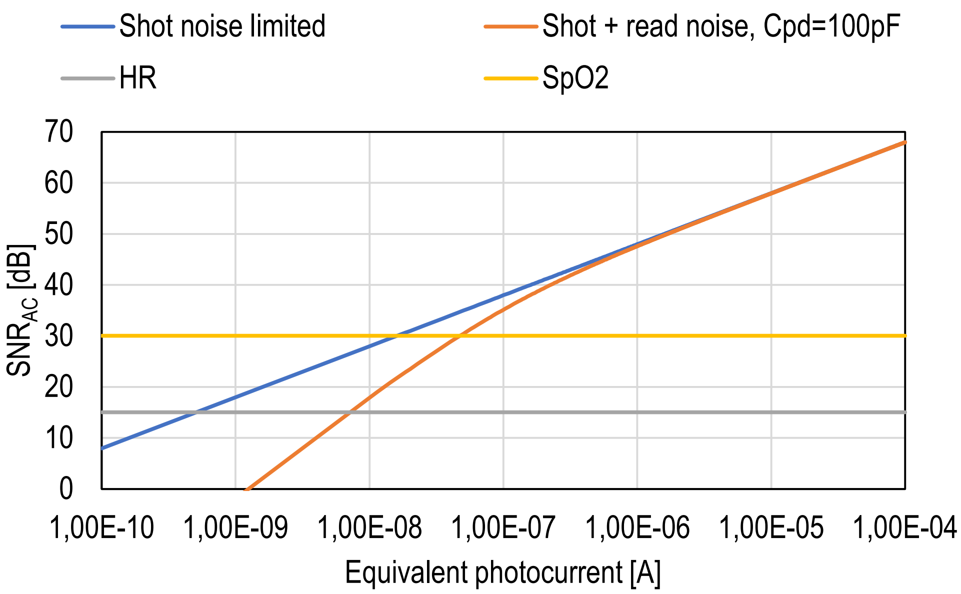

Figure 2: SNR_{AC} vs the photodiode equivalent photocurrent, at 1% PI, for two readout chains: first one shot noise limited and second one exhibiting a non negligible read noise. A 100 pF photodiode parasitic capacitance is considered for the read noise. The two horizontal lines define the general SNR requirements for HR and SpO2 (oxygen saturation) measurements

Depending on the PPG sensor use case, the requirements on the SNR_{AC} change. Let us consider two use cases, corresponding to two different SNR_{AC} requirements:

1. SNR_{AC} equal to 15 dB:
   An SNR_{AC} equal to 15 dB is enough to correctly measure the heart rate from a PPG signal. In this case, what would the advantage of a shot noise limited PPG readout chain be versus a standard one, exhibiting a not negligible read noise? Figure 2 shows that the target SNR_{AC} of 15 dB can be reached with more than an order of magnitude less photocurrent as compared to the case of the shot + read noise circuit. This means an order of magnitude lower LED power.

2. SNR_{AC} equal to 30 dB:
   An SNR_{AC} at least equal to 30 dB is needed to measure the oxygen saturation (SpO_2) from a PPG signal within 2 digits requirement, as requested by the regulatory bodies [1]. What would the advantage of a shot noise limited PPG readout chain be versus a standard one in the SpO_2 use case? Figure 2 shows that the target SNR_{AC} of 30 dB can be reached with roughly a factor of five less photocurrent as compared to the case of the shot + read noise circuit. This means a significant reduction in LED power consumption, especially considering that two LEDs are needed in the SpO_2 case.

We have shown so far the close relationship between the SNR_{DC} and the SNR_{AC}. It is key to extend as much as possible the former in order not to be limited by the latter, particularly under tight PI conditions. The ADC represents a big part of the complexity and power consumption of any PPG sensor module. Both the design complexity and the power consumption depend directly on the resolution of the ADC.

The SNR_{DC} that a PPG sensor can achieve is ultimately limited by its ADC resolution and can be expressed as:

$$SNR_{DC} = 6 \times resolution - 20\log(Noise).$$

Hence, the required resolution to achieve a target PPG SNR_{AC} can be expressed as:

$$resolution = 1/6 \times [20\log(Noise) + SNR_{AC} - 20\log(PI)].$$

Figure 3 shows the required ADC resolution as a function of the PI, considering the noise equal to 1 LSB. This figure demonstrates that the ADC resolution required to cope with a target PPG signal SNR strongly depends on the PI.

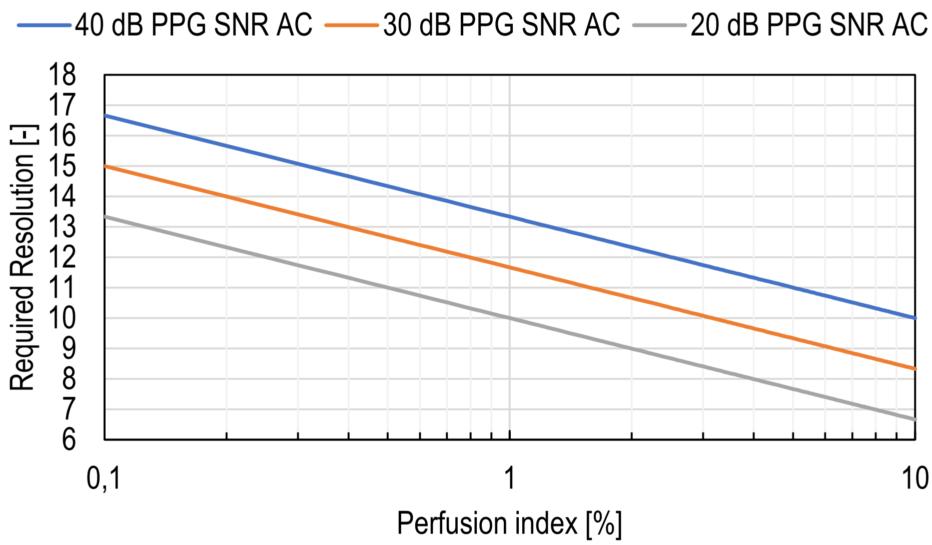

Figure 3: Required ADC resolution as a function of the PI for different target SNR values

Figure 3 also shows that, depending on the use case, a large ADC resolution may not be necessary. This is important to avoid unnecessary increases in the power consumption. For example, if one targets an SNR_{AC} of about 20 dB, for 1% minimum PI, an ADC resolution of less than 12 bit is needed.

References:

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