Application Note

Optimizing SNR in Photoelectric Smoke Detectors using TPS8802 and TPS8804

TEXAS INSTRUMENTS

ABSTRACT

Recent trends in smoke detectors are moving toward higher sensor accuracy with fewer false alarms using photoelectric sensing. Achieving high sensor accuracy requires low noise amplifiers and optimized signal filtering to maximize the sensor signal-to-noise ratio (SNR) with constrained power consumption. The TPS8802 and TPS8804 (TPS880x) integrate a photodiode amplifier and LED driver specialized for low power and low noise smoke detection. This report presents the TPS880x photoelectric sensor AFE architecture, discusses how to optimize the SNR in a system, and derives a model for the signal and noise in the system. This report explores three digital filtering techniques for processing the ADC samples: multiple sample averaging, digital matched filtering, and unconstrained filtering. Measurements verify the model accuracy and determine the effectiveness of each technique.

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1 Introduction

In a photoelectric smoke sensor, an LED periodically emits light into a chamber. The light scatters off smoke particles and enters a photodiode. The photodiode outputs a current proportional to the incident light, which is proportional to the smoke concentration. The LED current must be pulsed and regulated, and the photodiode current must be amplified with low noise and high linearity. Therefore, smoke detectors require a LED driver and photodiode amplifier to obtain an accurate signal from the sensor. With the signal amplified, an analog-to-digital converter (ADC) on the MCU captures samples of the signals and the MCU calculates the smoke concentration.

The TPS880x AFE integrates the regulators, drivers and amplifiers to interface the smoke detector's power supply, sensors, and microcontroller unit (MCU). The TPS880x has adjustable LED driver current, LED pulse width, amplifier bandwidth, amplifier gain, and output filter bandwidth. Each of these parameters, along with the ADC timing, affects the SNR. When all of these parameters are adjusted, reliable smoke sensing with only nanoamps of photodiode current is achieved.

This report analyzes how each of the system parameters affects the SNR. Modeling the system provides valuable insight on how to optimize the SNR. Measurements verify the trends in the model and provide configurations for users to start their designs.

2 SNR Optimization

2.1 SNR Overview

SNR is commonly defined as the ratio of signal power to noise power. In a smoke detector, the signal of interest is the smoke concentration, calculated from measurements of the photodiode current. Amplifying the photodiode current adds noise which makes the smoke concentration measurement fluctuate even if the actual smoke concentration is constant. Therefore, having high SNR is essential to quickly and accurately decide if the smoke concentration is at a dangerous level.

In this report, SNR is presented as the smoke measurement amplitude divided by the smoke measurement standard deviation. This metric provides the designer with the statistics of the smoke measurement. Because the smoke measurement amplitude is proportional to the smoke concentration, SNR increases with the smoke concentration. Therefore, the SNR in this report is specified at 1 nA photodiode current. The conversion from smoke concentration to photodiode current depends on the LED, photodiode, and chamber geometry. In general, the photodiode current is proportional to the LED current. To calculate the SNR at a different current, multiply the SNR by the new current and divide by 1 nA.

2.2 Smoke Concentration Measurement

A smoke concentration measurement follows this general procedure:

1. Enable the photo amplifier and analog multiplexer (AMUX) buffer.
2. Take one or more ADC measurements after the photo amplifier and AMUX settles. This measures the ambient light entering the photo chamber. ADC samples taken before the LED is enabled are referred to as base samples in this report.
3. Enable the LED.
4. Take one or more ADC measurements after the photo amplifier and AMUX settles. This measures the ambient light and scattered light in the photo chamber. ADC samples taken after the LED is enabled are referred to as top samples in this report.
5. Disable the LED, photo amplifier, and AMUX buffer.
6. Process the ADC measurements to determine the smoke concentration. The photo chamber responsivity must be known to obtain an accurate measurement.

The SNR of the smoke concentration measurement depends on many parameters in the system, including amplifier speeds, LED current, LED pulse width, ADC sample rate and digital filtering. These parameters can be adjusted to improve the SNR. The LED and photodiode parameters, such as quantum efficiency and half-angle, and the photo chamber geometry also have an effect on the SNR but are beyond the scope of this report. Table 2-1 lists various measurement configurations and the SNR at 1 nA of photodiode current. The SNR at 1 nA is reported here as a unitless ratio and can be converted to decibels by taking the base-10 logarithm and multiplying by 20. Table 2-1 provides a reference for users to design a smoke detector using the TPS880x AFE. The parameters in the table are discussed in Section 2.3 and Section 2.4. The configurations in Table 2-1 are selected from measurements in Section 4. Section 4 also outlines the measurement process.

Table 2-1. System Configurations and Measured SNR at 1 nA Photodiode Current

Config.	t_{LED} (µs)	τ_1 (µs)	τ_2 (µs)	N_{BASE}	N_{TOP}	t_{SAMP} (µs)	t_{TOP} (µs)	Filter	SNR at 1 nA
1	50	15	15	5	1	20	68	-	13.0
2	50	15	15	5	2	20	53	Average	15.6
3	100	15	15	10	1	20	91	-	18.9
4	100	59	60	10	1	20	129	-	25.7
5	100	15	15	10	5	20	48	Average	31.1
6	100	15	15	10	7	20	8	Matched	32.3
7	100	15	15	20	8	10	68	Average	33.1
8	200	59	60	20	1	20	216	-	42.5

2.3 Amplifier and LED Settings

Optimally amplifying the photodiode current requires careful selection of the amplifier gains, amplifier speeds, LED current and LED pulse width. The photodiode current can be as low as 1 nA, making the amplified signal highly susceptible to noise.

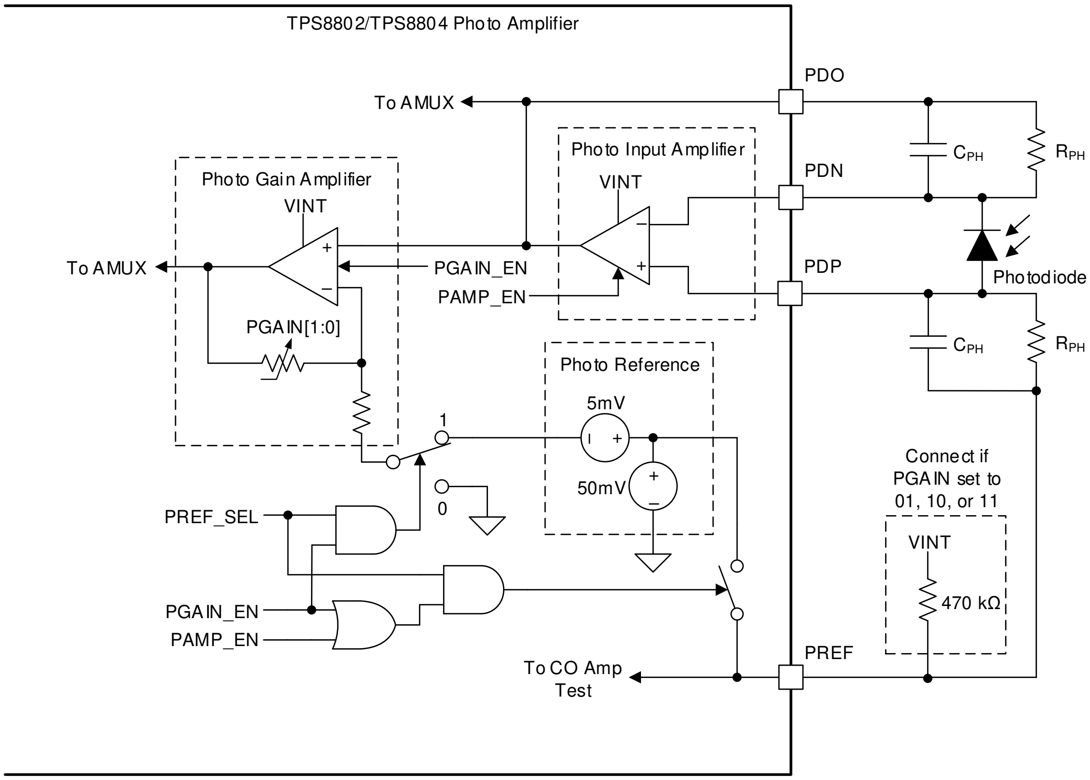


Figure 2-1. TPS880x Photo Amplifier Schematics

2.3.1 Photo Amplifier Gain

The first component to select is the photo input amplifier gain resistor R_{PH}. This resistor sets the transimpedance of the first stage amplifier. Resistance of less than 200 kΩ introduce thermal noise into the output, reducing SNR. Resistance of less than 5 MΩ limit the maximum speed of the amplifier and may require impractically low compensation capacitance. A resistance of 1.5 MΩ works in most applications and is a good resistance to start the design with. Select the photo input amplifier gain resistor and second stage gain such that the maximum photodiode current generates an output voltage of 2 V. This utilizes the full dynamic range of the TPS880x amplifiers and reduces ADC quantization noise. With thermal noise and quantization noise mitigated, the amplifier current noise is the primary contributor to the output noise. The photo input amplifier gain resistor equally amplifies the photodiode current and the amplifier current noise. In this condition, the R_{PH} resistance has a minimal effect on SNR.

2.3.2 Photo Amplifier and AMUX Speed

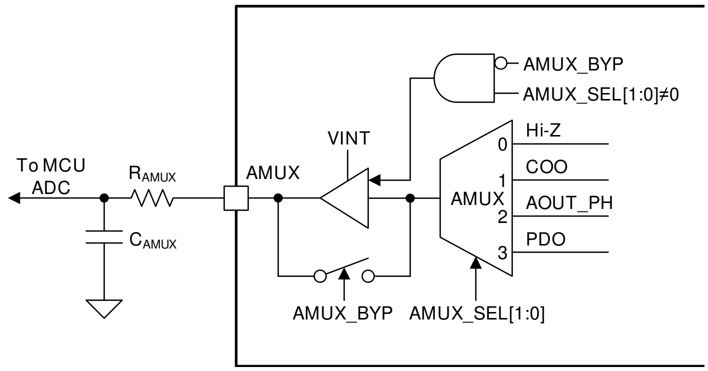


Figure 2-2. TPS880x AMUX Buffer Schematics

The optimal photo amplifier and AMUX speeds depend on the LED pulse width and ADC sample rate. The photo amplifier time constant τ_1 is equal to the gain resistor R_{PH} times C_{PH}. τ_1 is adjusted by varying C_{PH} once R_{PH} is selected. The AMUX time constant τ_2 is equal to the AMUX buffer resistance R_{AMUX} times C_{AMUX}. τ_2 is adjusted by varying R_{AMUX} after setting C_{AMUX} between 330 pF and 1nF. Adjusting the amplifier speeds is an effective way to improve the SNR. This is demonstrated with configurations 3 and 4 in Table 2-1.

The highest SNR for a fixed pulse width is achieved with a fast amplifier speed and fast ADC sample rate, then taking multiple ADC samples over the width of the photo pulse and averaging them together. For example, configuration 5 in Table 2-1 has a higher SNR than configuration 4 because a faster amplifier speed and multiple ADC samples are taken. If the ADC sample rate is slow, or if only one top ADC sample is taken, then a slow amplifier speed achieves the highest SNR. Using higher and lower speeds than shown in Table 2-1 may improve the SNR further.

2.3.3 LED Current and Pulse Width

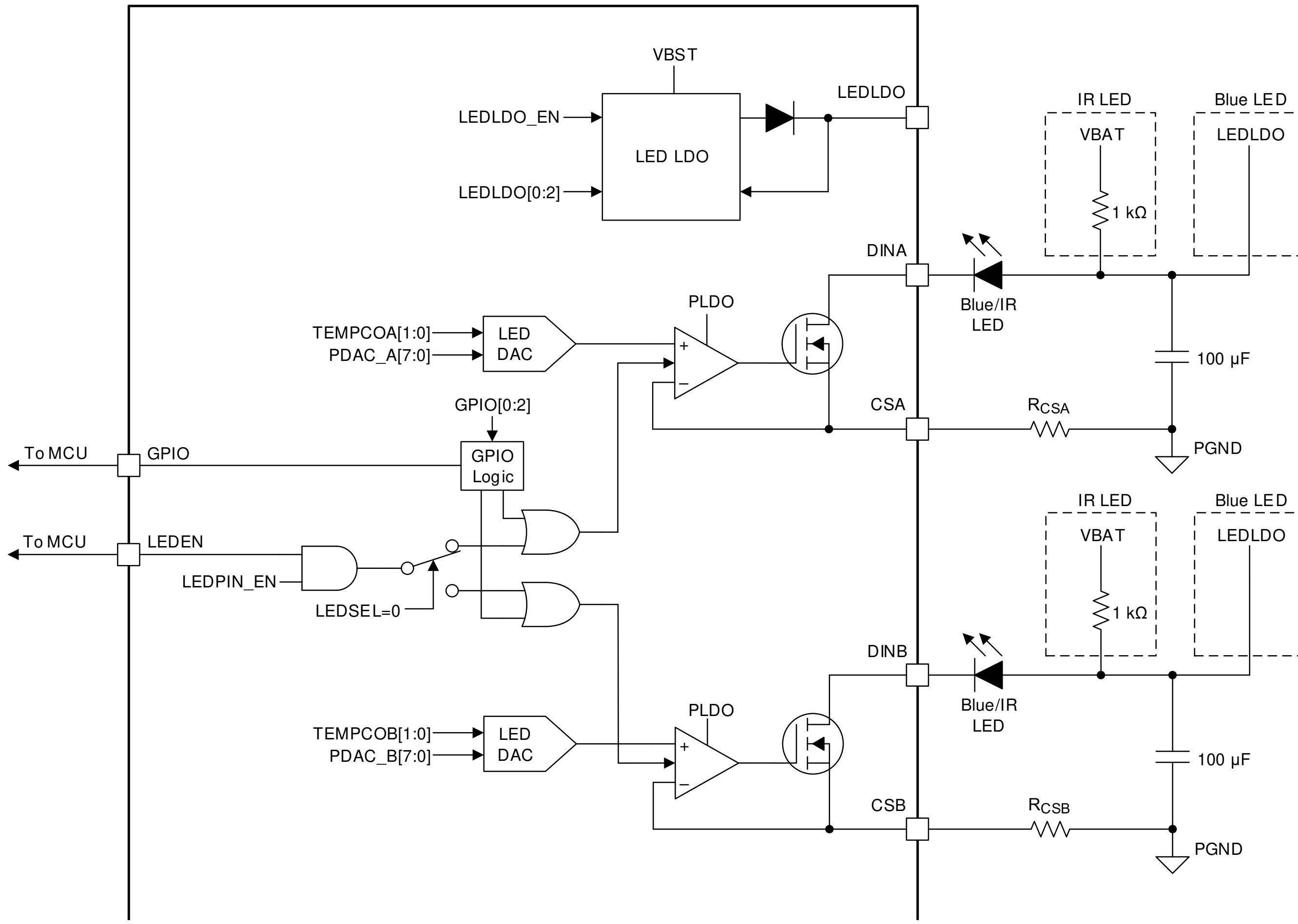


Figure 2-3. TPS880x LED Driver Schematics

Increasing the LED current and pulse width improves the SNR at the cost of increased power consumption. LED current directly increases the LED output intensity and the smoke sensitivity of the detector. Increasing the LED current is a simple and effective way to increase the SNR.

Increasing the LED pulse width improves the SNR by allowing the photodiode current to be amplified for more time. Table 2-1 demonstrates the improvement in configurations 1 and 3 and configurations 4 and 8, where t_{LED} is the LED pulse width. Increasing the LED pulse width and proportionally decreasing the amplifier speed also improves the SNR, shown in configurations 1 and 8.

For battery operated smoke detectors, increasing the LED current or pulse width may not be possible due to limited system power capacity. In this case, the LED current can be increased and the pulse width decreased to improve SNR while consuming the same amount of power. The benefit is small but evident when comparing configurations 1 and 4. The SNR and power consumption in configuration 1 is about half of configuration 4. If the LED current is doubled in configuration 1, the power consumption is the same as configuration 4 and the SNR is slightly higher than configuration 4. Since the 50 µs pulse width was tested with only one τ_1 and τ_2 combination, it is likely that the SNR of configuration 1 can be improved by varying τ_1 and τ_2.

If multiple ADC samples are taken, fewer top ADC samples can be taken with shorter pulse widths. This may reduce the benefit of using a shorter pulse width. Always take measurements to confirm the SNR improvement when modifying system parameters.

Increasing the LED current increases the LED forward voltage and the LED power consumption. The LED power consumption is equal to the LED current times the LED forward voltage. Because the TPS880x uses a linear regulating LED driver, the power consumed by the driver and LED is equal to the LED current times the LED supply voltage. In applications where the SNR is too low and power consumption must be minimized, it is optimal to first increase the LED current until a higher LED supply voltage is required, then increase the LED pulse width. At high LED currents, the LED output power per input current and lifespan drops.

The TPS880x LED driver has a propagation delay and rise time that limits the minimum pulse width. It is recommended to use a pulse width longer than 20 microseconds to mitigate propagation delay and rise time variation effects on the signal.

2.4 ADC Sampling and Digital Filtering

2.4.1 ADC Sampling

Taking multiple ADC samples is an effective way to improve the SNR. Comparing configurations 3 and 5 in Table 2-1, the SNR is significantly improved by averaging multiple top ADC samples. The number of top ADC samples is displayed as N_{TOP} and the time of the first top ADC sample is t_{TOP}. Faster ADC sample rates allow more samples to be taken at the top of the photo pulse and improve the SNR further. This is demonstrated in configurations 5 and 7. Table 2-1 displays the time between ADC samples as t_{SAMP}.

Higher ADC resolutions improve the SNR to a limit. Figure 4-21 displays the effect of varying the ADC LSB size for a 260 mV amplitude pulse. The SNR drops when the ADC least significant bit (LSB) is greater than 5 mV. In this case, a 10-bit ADC with a 2 V to 3 V full-scale voltage is sufficient for maximizing SNR.

Taking multiple ADC samples of the signal before the LED is enabled is effective in systems that measure the ambient light level before the LED is enabled. This is displayed as N_{BASE} in Table 2-1. The benefit is shown in Figure 4-20. Because the LED is not enabled for these ADC samples, low power is consumed when taking the multiple ADC samples before the LED is enabled.

If the ADC sample rate is different from the examples in Table 2-1, take samples for the same amount of time as done in Table 2-1. For example, if a 5 μs t_{SAMP} is used with τ_1 and τ_2 set to 15 μs, take 40 base samples and 16 top samples.

2.4.2 Digital Filtering

Averaging the multiple ADC samples together is an effective way to process the ADC samples. Using a digital matched filter improves the SNR further. The matched filter weighs each sample by the noiseless DC-removed waveform voltage before averaging the samples together. An example DC-removed waveform and corresponding filter weights are shown in Figure 4-7 and Figure 4-8. The filter weights can be obtained dynamically by averaging measured each DC-removed ADC sample across multiple pulses. While the matched filter is more complex than the averaging filter, it can be used to increase the SNR without affecting power consumption.

It is shown in Figure 4-13 that other digital filters can improve the SNR further. The unconstrained filter has weights optimized for SNR. An example of the unconstrained filter weights is shown in Figure 4-8. The unconstrained filter is included to demonstrate how SNR can be improved beyond matched filtering.

3 System Modeling

Modeling the photo amplifier system explains why the methods discussed in Section 2 improve the SNR. The model is included here to further the user's understanding of the system and provide a framework for further optimization.

3.1 Impulse Response

Calculating the impulse response of the system can be done by modeling the photo input amplifier, photo gain amplifier, and AMUX buffer.

3.1.1 Photodiode Input Amplifier Model

Using a photodiode model consisting of a capacitor and current source, the photo input amplifier system can be modeled as a combination of linear circuit elements shown in Figure 3-1. To simplify the analysis, the PREF photo reference is approximated as a small-signal ground, and the two photo resistors and capacitors are combined in series. The simplified circuit is shown in Figure 3-2. The op-amp is modeled with frequency-dependent open-loop gain A(s). The op-amp open-loop gain is 1 at the gain-bandwidth frequency f_{GBW}.

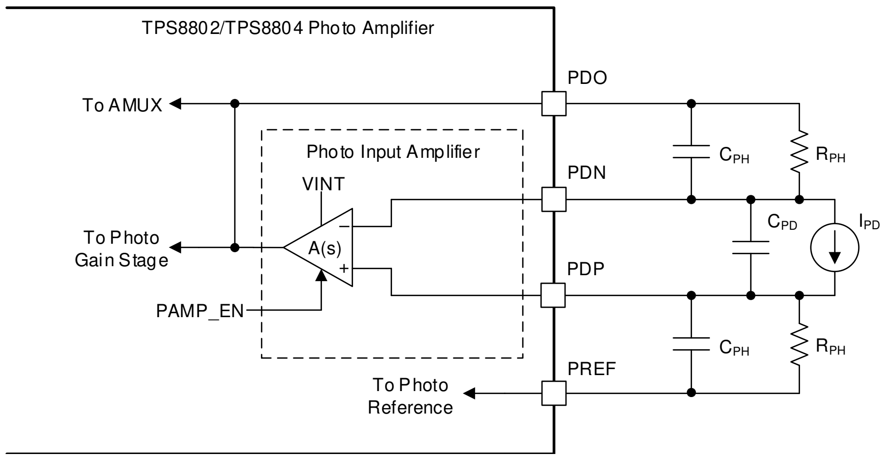


Figure 3-1. Photo Input Amplifier Model

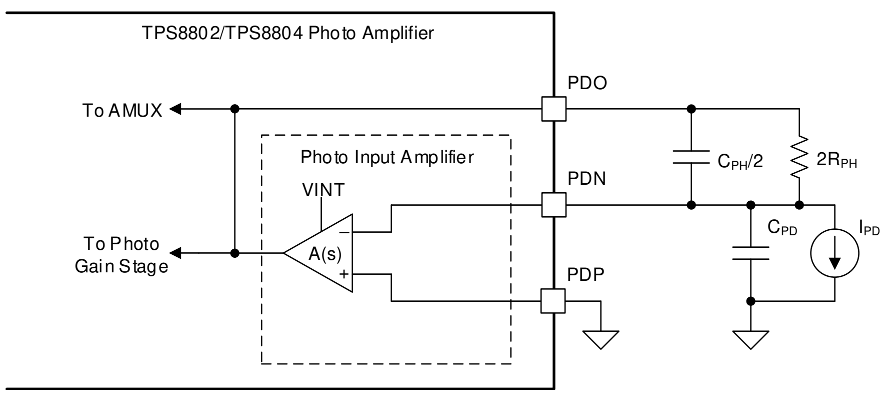


Figure 3-2. Simplified Photo Input Amplifier Model

Equation 1 shows the open loop transfer function from PDO to PDN. This equation provides insight on how to stabilize the feedback loop. The compensation capacitor C_{PH} must be sized to place the zero frequency below the closed loop unity gain frequency for sufficient phase margin. A phase margin of over 70° prevents overshoot and reduces noise on the output. This is achieved when the zero frequency is less than the unity gain frequency by at least a factor of 3. The zero frequency and unity gain frequency are calculated in Equation 2 and Equation 3. These two equations set a lower limit on the compensation capacitance, shown in Equation 4, using the assumption that C_{PH} is less than C_{PD}. The photo input amplifier has a minimum unity gain bandwidth f_{GBW} of 1 MHz. Set f_{GBW} to 1 MHz when calculating the minimum compensation capacitance.

$$\frac{V_{PDN}}{V_{PDO}} = \frac{1 + s \times R_{PH} \times C_{PH}}{1 + s \times R_{PH} \times (C_{PH} + 2 \times C_{PD})} \quad (1)$$

$$f_Z = \frac{1}{2 \times \pi \times R_{PH} \times C_{PH}} \quad (2)$$

$$f_{UG} \cong \frac{f_{GBW} \times C_{PH}}{2 \times C_{PD} + C_{PH}} \quad (3)$$

$$C_{PH} > \sqrt{\frac{3 \times C_{PD}}{\pi \times R_{PH} \times f_{GBW}}} \quad (4)$$

The compensation capacitance sets the closed loop bandwidth of the amplifier. Solving the closed loop amplifier output PDO in terms of the input current I_{PD} results in Equation 5. The Equation 5 denominator approximately equals 1 at frequencies below the unity gain frequency calculated in Equation 3. In this condition, Equation 5 can be simplified to Equation 6. Equation 6 demonstrates that the photo amplifier output is approximately equal to the photocurrent scaled by the gain resistors and low-pass filtered by the compensation capacitors. Above the unity gain frequency, additional low-pass filtering occurs on the signal.

$$V_{PDO(SIG)} = \frac{I_{PD} \times \frac{2 \times R_{PH}}{1 + s \times R_{PH} \times C_{PH}}}{1 + \frac{1 + s \times R_{PH} \times (C_{PH} + 2 \times C_{PD})}{(1 + s \times R_{PH} \times C_{PH}) \times A(s)}} \quad (5)$$

$$V_{PDO(SIG)} \cong I_{PD} \times \frac{2 \times R_{PH}}{1 + s \times R_{PH} \times C_{PH}} \quad (6)$$

3.1.2 Photodiode Gain Amplifier and AMUX Buffer Model

The photo gain amplifier can be modeled as an ideal voltage amplifier at the bandwidths and gains explored in this report. In applications where lower first stage gains or higher bandwidths are used, additional measurements may be required to accurately model the photo gain amplifier.

The AMUX buffer has sufficient bandwidth and capacitance driving capability to be modeled as an ideal buffer. The RC filter can also be modeled as ideal.

3.1.3 Combined Signal Chain

The signal at the buffered AMUX output can be calculated using the models for each stage, as shown in Equation 7. τ_1 and τ_2 represent the photo input amplifier and AMUX filter time constants, respectively. Taking an integral and inverse Laplace transform of Equation 7 results in the time-dependent step response in Equation 8. Here, H(t) is the Heaviside step function, taking the value 0 for negative inputs and 1 for non-negative inputs. The step response assumes that the photocurrent is stepped from 0 to I_{PD} when t is equal to 0. The step response calculation in Equation 8 is undefined when τ_1 and τ_2 are equal. In this case, the limit can be taken to solve for the step response.

$$V_{BUF} = \frac{V_{PDO} \times G_{PGAIN}}{1 + s \times R_{AMUX} \times C_{AMUX}} = \frac{I_{PD} \times 2 \times R_{PH} \times G_{PGAIN}}{(1 + s \times \tau_1) \times (1 + s \times \tau_2)} \quad (7)$$

$$V_{BUF(STEP)}(t) = I_{PD} \times 2 \times R_{PH} \times G_{PGAIN} \times \left(1 + \frac{\tau_1}{\tau_2 - \tau_1} \times e^{\frac{-t}{\tau_1}} + \frac{\tau_2}{\tau_1 - \tau_2} \times e^{\frac{-t}{\tau_2}}\right) \times H(t) + V_{DC} \quad (8)$$

With the step response calculated, the response to a rectangular pulse input is calculated in Equation 9, where t_{LED} is the LED pulse width. Equation 10 and Equation 11 calculate the baseline DC voltage of the buffered photo signal with and without a 470 kΩ resistor installed on PREF. $V_{PDO(OFS)}$ is the DC offset caused by the photo input amplifier and $V_{PGAIN(OFS)}$ is the DC offset caused by the photo gain amplifier. Because there is a propagation delay on the TPS880x LED driver, the output may be shifted from when the LED is enabled.

$$V_{BUF(PULSE)}(t) = V_{BUF(STEP)}(t) - V_{BUF(STEP)}(t - t_{LED}) + V_{DC} \quad (9)$$

$$V_{DC} = 50\text{ mV} + \left(5\text{ mV} + V_{PDO(OFS)} + V_{PGAIN(OFS)}\right) \times G_{PGAIN} \tag{10}$$

$$V_{DC(470k\Omega)} = 70\text{ mV} + \left(7\text{ mV} + V_{PDO(OFS)} + V_{PGAIN(OFS)}\right) \times G_{PGAIN} \tag{11}$$

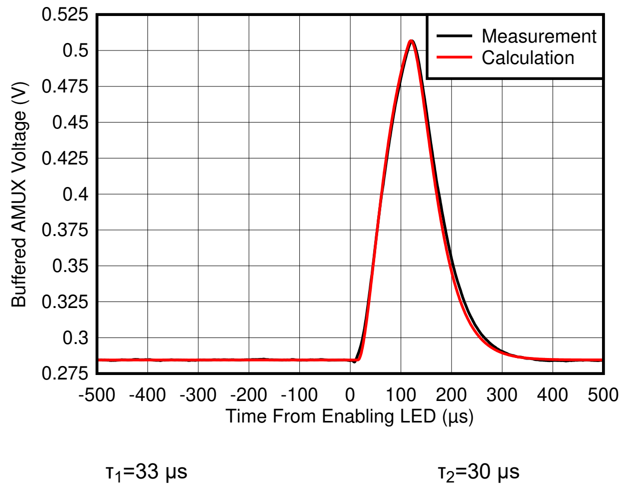


Figure 3-3. Measurement and Amplitude-Adjusted Calculation of a 100 µs LED Photo Pulse

3.2 Noise Modeling

3.2.1 Noise Sources

The noise generated by the photo input amplifier and gain resistors R_{PH} generally exceed the noise generated by the photo gain stage, AMUX buffer, and photodiode. The photo amplifier schematics with noise sources modeled is displayed in Figure 3-4. The photo input amplifier is modeled with input voltage and current noises. Op-amp voltage noise is displayed as V_{NAMP} and current noises are displayed as I_{NAMP}. The two amplifier current noises are assumed equal, as the op-amp has voltage feedback.

Thermal noise is a noise source that naturally occurs in resistors. Thermal noise is modeled as a voltage noise in series with the resistor or equivalently a current noise in parallel with the resistor. The thermal noise sources in the photo input amplifier stage are shown in Figure 3-4 as I_{NRPH}. Here, a current noise is used because the current-to-voltage amplifier transfer function is calculated in Equation 5. The thermal noise at 300 K is calculated in Equation 12.

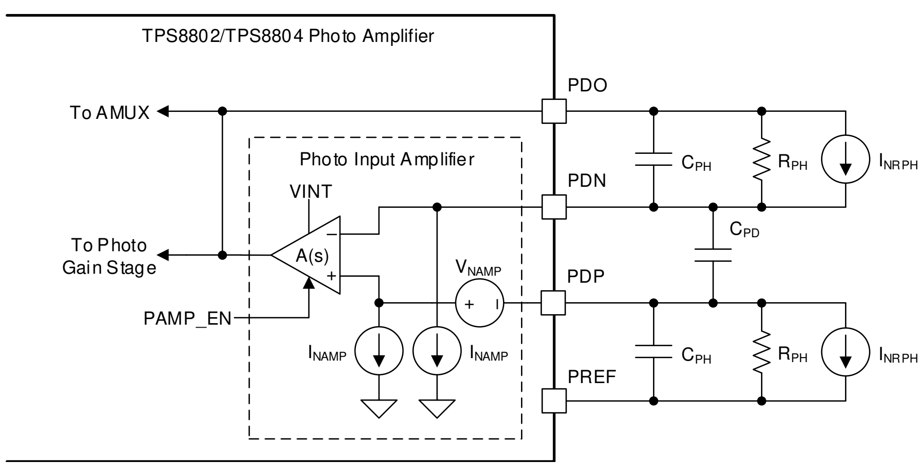


Figure 3-4. Photo Input Amplifier With Noise Sources Modeled

$$I_{NRPH} = \frac{0.13}{\sqrt{R_{PH}}} \frac{\text{nA}}{\sqrt{\text{Hz}}} \tag{12}$$

3.2.2 Output Voltage Noise Model

The PDO voltage noise density is calculated using the op-amp and resistor noise models, shown in Equation 13. Independent noise sources are combined by taking the root-sum-of-squares. Equation 14 simplifies the output noise by dividing the Equation 13 noise voltage density by the signal voltage calculated in Equation 5. Equation 14 is used to identify the dominant source of noise in the amplifier.

$$S_{PDO(NOISE)} = \frac{\sqrt{\left(2 \times I_{NAMP}^2 + 2 \times I_{NRPH}^2\right) \times \left(\frac{R_{PH}}{1 + s \times R_{PH} \times C_{PH}}\right)^2 + V_{NAMP}^2 \times \left(\frac{1 + s \times R_{PH} \times (C_{PH} + 2 \times C_{PD})}{1 + s \times R_{PH} \times C_{PH}}\right)^2}}{1 + \frac{1 + s \times R_{PH} \times (C_{PH} + 2 \times C_{PD})}{(1 + s \times R_{PH} \times C_{PH}) \times A(s)}} \quad (13)$$

$$\frac{S_{PDO(NOISE)}}{V_{PDO(SIG)}} = \frac{1}{I_{PD}} \times \sqrt{\left(\frac{I_{NAMP}}{\sqrt{2}}\right)^2 + \left(\frac{I_{NRPH}}{\sqrt{2}}\right)^2 + \left(V_{NAMP} \frac{1 + s \times R_{PH} \times (C_{PH} + 2 \times C_{PD})}{2 \times R_{PH}}\right)^2} \quad (14)$$

The resistor noise and amplifier voltage noise is less than the amplifier current noise when R_{PH} is greater than approximately 200 kΩ, based on measurements of the voltage and current noise density. In most applications, R_{PH} is greater than 200 kΩ and the resistor noise and voltage noise are negligible.

The buffered photo RMS voltage noise is calculated in Equation 15 using the amplifier current noise as the only noise source. The amplifier current noise is assumed to be white. The buffered photo signal model in Equation 7 is used to calculate the buffered photo noise density in Equation 15. Integrating the noise density across the frequency spectrum calculates the RMS noise. The result demonstrates that the output noise increases with the amplifier gain and decreases with the root-sum of time constants.

$$V_{BUF(NOISE)} = \sqrt{\int_0^{\infty} 2 \times \left|\frac{I_{NAMP} \times R_{PH} \times G_{PGAIN}}{(1 + j \times 2 \times \pi \times f \times \tau_1) \times (1 + j \times 2 \times \pi \times f \times \tau_2)}\right|^2 \times df} = \frac{I_{NAMP} \times R_{PH} \times G_{PGAIN}}{\sqrt{2 \times (\tau_1 + \tau_2)}} \quad (15)$$

3.2.3 ADC Quantization Noise

ADC quantization noise is a noise source caused by rounding the photo signal to the nearest least significant bit (LSB) when digitizing the signal. Ensure the quantization noise level is less than the photo noise level to maximize SNR. This can be done by increasing the gain in the photo input amplifier or photo gain stage. ADC quantization noise is calculated in Equation 16.

$$V_{Q(RMS)} = \frac{LSB}{\sqrt{12}} \quad (16)$$

3.3 SNR Calculation

3.3.1 Single ADC Sample

The simplest way to measure the photo signal is to take an ADC sample of the buffered AMUX output when the photo chamber LED is enabled. The output level is proportional to the concentration of smoke and one ADC sample is theoretically sufficient to determine the smoke concentration. However, because of variations in offset voltages and leakage currents, the base DC voltage of the photo signal varies from part to part. Additionally, taking multiple ADC samples reduces the measurement noise. It is recommended to take two groups of ADC samples: one group before the LED is enabled to measure the pulse base voltage and one group after the LED is enabled to measure the pulse top voltage. Processing the two groups of ADC samples cancels the baseline DC voltage and the retains the signal amplitude.

3.3.2 Two ADC Samples

Using one ADC sample for the base voltage and one ADC sample for the top voltage results in the SNR calculated in Equation 17. The top signal is calculated using the Equation 9 buffered photo signal pulse sampled at time t. The signal noise is calculated using the Equation 15 buffered AMUX output noise voltage divided by the square root of two. Sampling the signal at the peak maximizes the SNR. The peak of the signal is approximately t_{LED}, and by sampling the signal at time t_{LED}, Equation 17 simplifies to Equation 18. Equation 18 provides the key insight that increasing t_{LED}, τ_1 and τ_2 together by a constant factor improves the SNR by the square root of the factor.

$$SNR_2 = \frac{2 \times I_{PD} \times \sqrt{\tau_1 + \tau_2}}{I_N} \times \left(V_{BUF(PULSE)}(t) - V_{DC}\right) \quad (17)$$

$$SNR_2 \cong \frac{2 \times I_{PD} \times \sqrt{\tau_1 + \tau_2}}{I_N} \times \left(1 + \frac{\tau_1}{\tau_2 - \tau_1} \times e^{\frac{-t_{LED}}{\tau_1}} + \frac{\tau_2}{\tau_1 - \tau_2} \times e^{\frac{-t_{LED}}{\tau_2}}\right) \quad (18)$$

Improving the SNR by increasing t_{LED}, τ_1 and τ_2 comes at the cost of increased power consumption. Because low power consumption is essential for smoke alarms, it is desirable to optimize the SNR without increasing power consumption. The LED pulse energy consumption is calculated in Equation 19. Dividing Equation 18 by Equation 19 results in Equation 20, the SNR per unit energy (SNRE). The photodiode current is proportional to the LED current, therefore the SNRE is relatively unaffected by changes in LED current.

$$E_{LED} = t_{LED} \times V_{LED} \times I_{LED} \quad (19)$$

$$SNRE_2 \cong \frac{2 \times I_{PD} \times \sqrt{\tau_1 + \tau_2}}{I_N \times t_{LED} \times V_{LED} \times I_{LED}} \times \left(1 + \frac{\tau_1}{\tau_2 - \tau_1} \times e^{\frac{-t_{LED}}{\tau_1}} + \frac{\tau_2}{\tau_1 - \tau_2} \times e^{\frac{-t_{LED}}{\tau_2}}\right) \quad (20)$$

Equation 20 is maximized in two steps. First, t_{LED} is held constant and the optimal τ_1 and τ_2 are numerically calculated using a nonlinear programming solver fminsearch in MATLAB. Setting τ_1 and τ_2 to 0.31 times the LED pulse length maximizes the SNR. Next, t_{LED} is varied with τ_1 and τ_2 set to 0.31 times t_{LED}. The SNRE increases as t_{LED}, τ_1 and τ_2 decrease, therefore the SNRE is maximized when t_{LED} is minimized. This result explains why shorter pulse lengths with higher LED currents can have a higher SNR than longer pulse lengths with lower LED currents. If τ_1 and τ_2 are equal and fixed while t_{LED} is varied, the optimal solution for t_{LED} is 1.8 τ_1.

Common methods set τ_1 and τ_2 below 0.2 t_{LED} to allow the signal to settle before taking the measurement or set τ_1 above t_{LED} to integrate the photodiode signal. Both of these methods do not have as high of an SNR compared to when τ_1 and τ_2 are set to 0.31 t_{LED}. Setting τ_1 and τ_2 to 0.2 t_{LED} compared to 0.31 t_{LED} has 14% higher amplitude and 25% higher noise. Setting τ_1 and τ_2 to t_{LED} compared to 0.31 t_{LED} has 58% lower amplitude and 44% lower noise.

3.3.3 Multiple Base ADC Samples

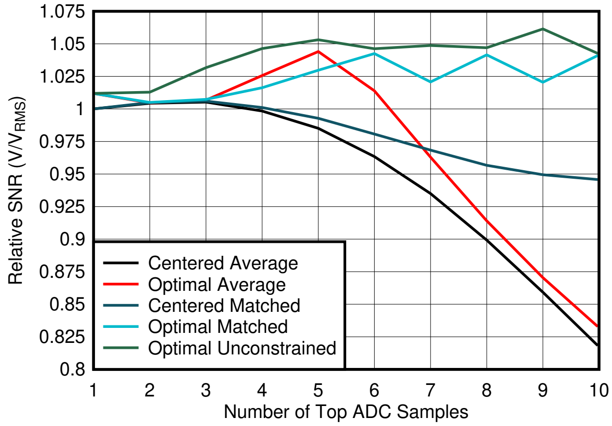
Calculating the RMS noise in Equation 17 involves a factor of square root of two caused by the root-sum-square of two ADC samples noise. One of these ADC samples is used to measure the base voltage of the photo amplifier signal and the other is used to measure the top voltage. If multiple ADC samples are used to measure the base voltage, the signal measurement dominates the total noise, improving the SNR by the square root of two. Taking multiple base ADC samples is a simple way to improve the SNR from the two ADC sample measurement.

3.3.4 Multiple Top ADC Samples

Taking multiple top ADC samples is an effective way to improve the SNR. By digitally processing the ADC samples, additional filtering is applied to the measurement. Three digital processing methods are investigated: average filtering, matched filtering, and unconstrained filtering. Average filtering is performed by averaging the ADC samples at the top of the pulse. Matched filtering is performed by scaling each sample by the noiseless DC-removed voltage at each sample, then summing the result. Unconstrained filtering is performed by scaling each sample by an optimized weight, then summing the result. Numerical calculation can be used to calculate the SNR with multiple top ADC samples.

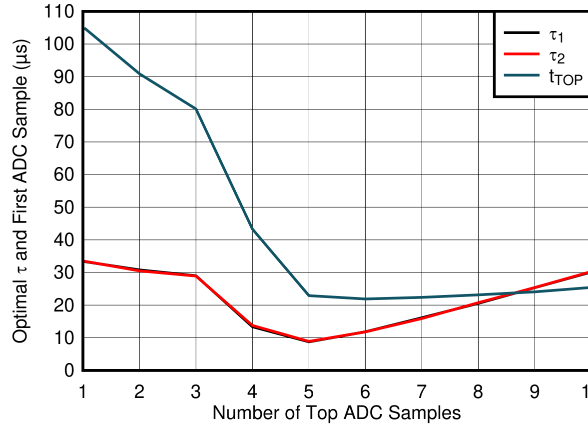
3.3.5 Multiple ADC Sample Simulation

A simulation of the smoke measurement system is implemented in MATLAB. A nonlinear programming solver, fminsearch, optimizes the ADC timing, amplifier time constants, and unconstrained filter weights. The result of the optimization for a 100 µs LED pulse and 20 µs ADC sampling rate is shown in Figure 3-5. The average and matched filter have initial parameters of τ_1 and τ_2 set to 0.31 times t_{LED} and the ADC samples centered on t_{LED}. Unconstrained filtering improves the SNR the most, by 6%, followed by matched filtering and average filtering at 4%. Each filter type also has a trend: as the number of ADC samples increases, the optimal τ_1 and τ_2 decreases, as shown in Figure 3-6. These trends are visible in the measurements as shown in Section 4.



t_{LED}=100 µs t_{SAMP}=20 µs

Figure 3-5. Comparison of Simulated Digital Processing Methods



t_{LED}=100 µs t_{SAMP}=20 µs

Figure 3-6. Simulated Optimal Averaging Filter Parameters

4 SNR Measurements

4.1 Measurement Procedure

The SNR of eight different configurations using three digital filtering methods is measured to identify optimal SNR techniques and verify the trends in the calculations. For each measurement, the R_{PH} gain resistors are 1.5 MΩ, gain stage amplification is 32.25, AMUX buffer capacitor is 1 nF, and the C_{PH} compensation capacitor and AMUX buffer resistor are varied to achieve the $τ_1$ and $τ_2$ in Table 4-1. A photoelectric smoke sensor from a commonly available smoke alarm is attached to a TPS8802EVM and sealed to prevent dust from affecting the signal level. The photodiode signal is generated from internal reflections in the chamber. The photodiode current is estimated to be 2.7 nA. All tests use a 3.0 V VBAT supply and 100 mA LED current, and the photodiode capacitance is measured to be 51 pF.

The noise is measured under two system conditions. The ideal system is powered with a 3.0 V supply connected to VBAT, has the photo amplifier continuously enabled and a signal generator connected to LEDEN to enable the LED. The real system uses a MSP430F5529 Launchpad to enable the photo amplifier, LED, and boost converter to replicate the conditions of a real smoke alarm with a 2.0 V supply voltage on VBAT. The boost converter is briefly enabled before enabling the LED to charge the LED supply and VCC capacitors.

The buffered AMUX voltage is probed with an oscilloscope to capture 100 kilosamples at 100 megasamples per second. 100 waveforms of each condition are captured. The samples are centered on the LED_EN rising edge, and the LED_EN pulse is extended by 15 µs to accommodate for the TPS880x LED driver propagation delay. This captures 500 µs of the signal before the LED is enabled and 500 µs after the LED is enabled. The samples are imported into MATLAB, where they are processed to simulate a microcontroller's ADC.

Table 4-1. Eight Measurement Configurations

#	t_{LED} (µs)	$τ_1$ (µs)	$τ_2$ (µs)	System
1	50	15	15	Ideal
2	100	15	15	Ideal
3	100	33	15	Ideal
4	100	33	30	Ideal
5	100	33	30	Real
6	100	59	30	Ideal
7	100	59	60	Ideal
8	200	59	60	Ideal

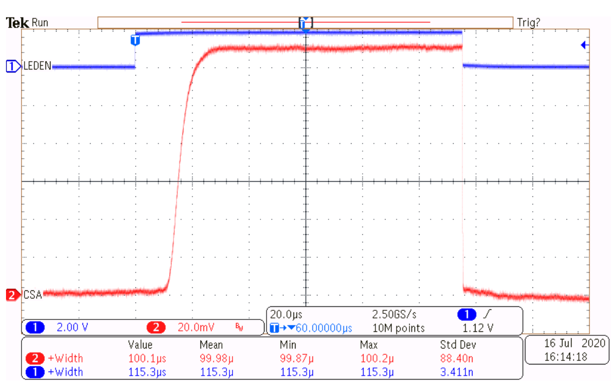


Figure 4-1. LEDEN and CSA Voltage (LED Current) for a 100 µs LED Pulse

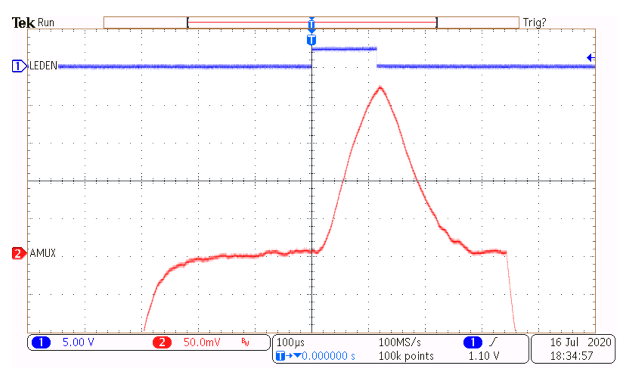


Figure 4-2. Buffered AMUX Pulse With Real Alarm Conditions

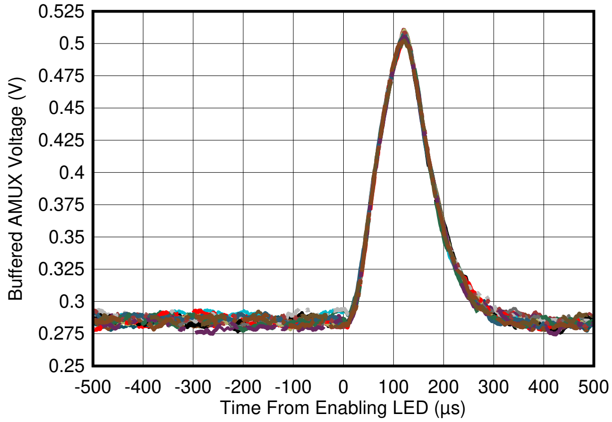


Figure 4-3. 20 of 100 Waveform Captures of Configuration 4

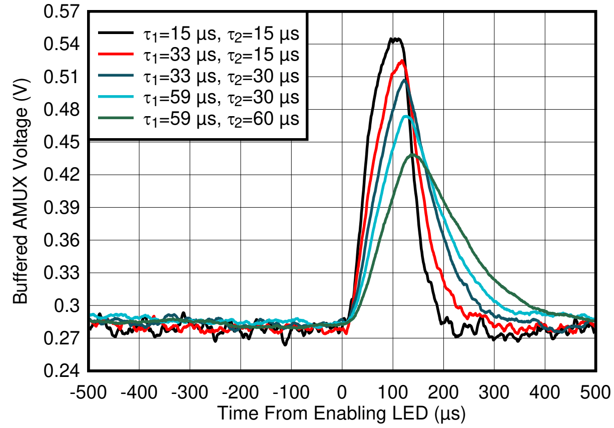


Figure 4-4. Single Waveform Captures of Each Time Constant

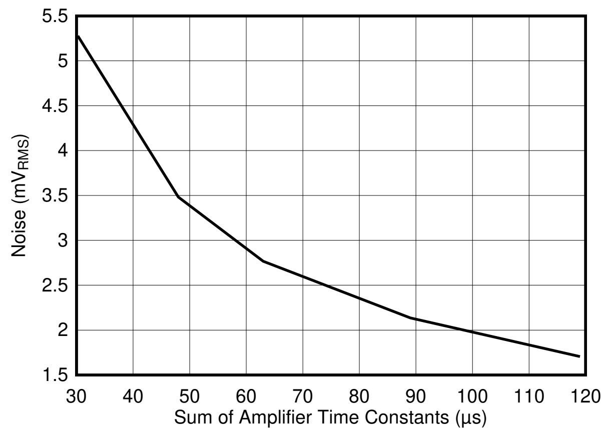


Figure 4-5. Measured Noise Level of Each Time Constant

4.2 Measurement Processing

In MATLAB, each waveform is convolved with a symmetric 21-point (210 ns) Hann window to reduce quantization noise caused by the 8-bit oscilloscope ADC. Samples are selected from the waveform using four parameters: first top sample time t_{TOP}, sampling time interval t_{SAMP}, number of top samples N_{TOP}, and number of base samples N_{BASE}. The base samples are selected starting at time zero, when the LED is enabled, and moving backward in time by t_{SAMP} increments. The number of base samples used in each SNR calculation is shown in Equation 21. This number sufficiently causes the DC voltage measurement noise to not dominate the total measurement noise.

$$N_{BASE} = \left\lceil 2 \times \frac{t_{LED}}{t_{SAMP}} \right\rceil \tag{21}$$

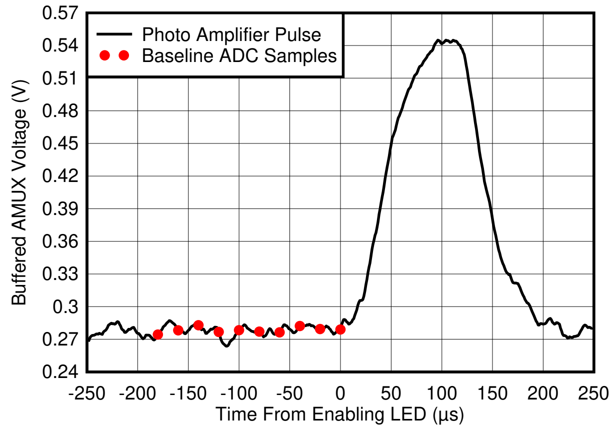


Figure 4-6. Photo Amplifier Signal With Base ADC Samples Highlighted

Each top sample is subtracted by the average of the base samples. This removes the DC level on the signal. The DC removed signal and ADC samples is shown in Figure 4-7. Two sets of ADC samples are shown: a set centered on the time when the LED is disabled, and an optimal set for maximizing SNR.

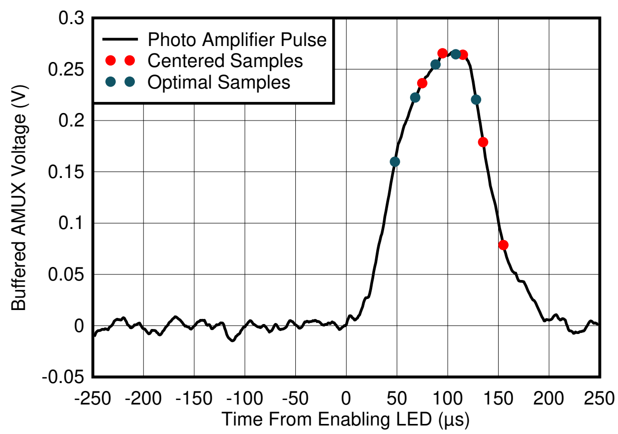


Figure 4-7. DC Removed Photo Amplifier Signal With Top ADC Samples Highlighted

Each sample is then scaled by a weight corresponding to the filter used. The averaging filter has equal weights, the matched filter has weights proportional to the noiseless DC-removed pulse shape, and the unconstrained filter can have any weight.

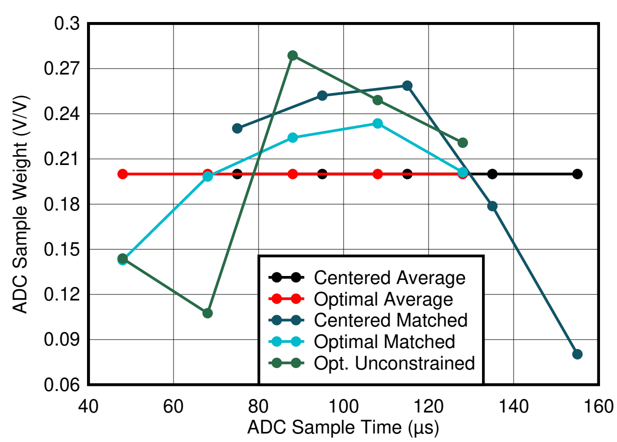


Figure 4-8. Centered and Optimized Digital Filter Weights and ADC Timing

The weighted samples are added together to obtain the signal amplitude. The signal amplitude is obtained for each of the 100 waveforms measured by the oscilloscope.

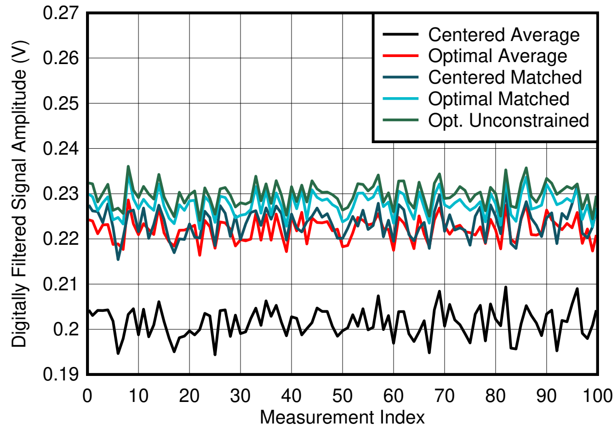


Figure 4-9. Signal Amplitude After Applying Centered and Optimized Digital Filters

The mean value of the signal amplitude across each waveform is the signal level, and the standard deviation of the signal amplitude across each waveform is the noise level. Dividing the signal level by the noise level calculates the signal-to-noise ratio. The SNR is then divided by the 2.7 nA photodiode current to obtain the SNR at 1 nA photodiode current. The SNR at 1 nA allows anyone to calculate the SNR of the photodiode signal in a system if the system's photodiode current is known. The SNR at 1 nA is reported here as a unitless ratio and can be converted to decibels by taking the base-10 logarithm and multiplying by 20.

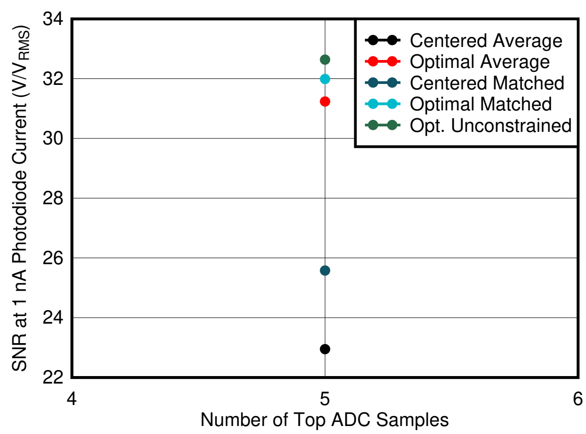


Figure 4-10. SNR at 1 nA Calculated From the Mean and Standard Deviation of Signal Amplitudes

The process is repeated varying different parameters in the system. For example, the data in Figure 4-10 is a portion of the data in Figure 4-13. The rest of the data in Figure 4-13 is collected by varying the number of ADC samples used.

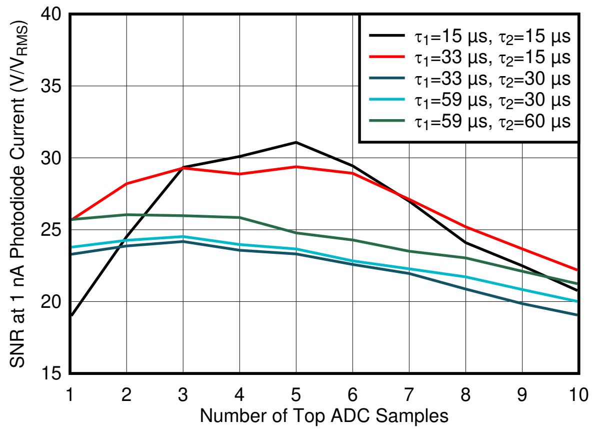
This method of calculating signal-to-noise ratio is formulated into a function and passed to a nonlinear programming solver fminsearch to optimize t_{TOP} and the unconstrained filter weights. The solver requires an initial guess for the optimized parameters. The first sample time is initialized such that the signal samples are centered on the time when the LED is disabled. The unconstrained filter weights are initialized to the matched filter weights. A first pass optimization is performed by varying the first sample time by $t_{LED}/2$ in 1 µs steps and recording the first sample time that achieves the best SNR. This first sample time is then used as the initial guess in the solver. The solver always finds a solution equal to or better than the initial guess, but may not find the optimal configuration.

4.3 Measurement Results

All SNR measurements are divided by the measured 2.7 nA photodiode current to obtain the SNR at 1 nanoamp photodiode current. To calculate the SNR at a different current, multiply the SNR by the new current and divide by 1 nA.

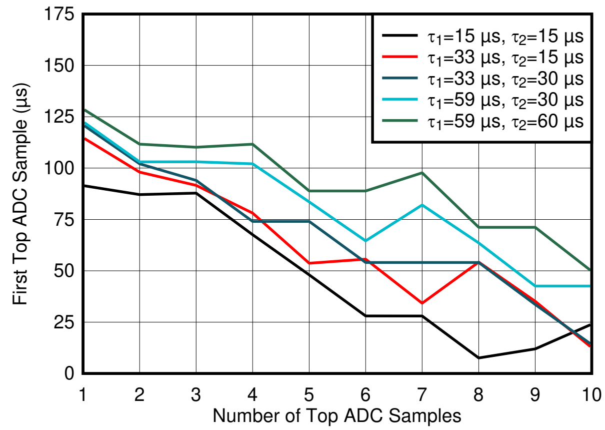
4.3.1 Varying Amplifier Speeds

Figure 4-11 shows the SNR at 1 nA with varying time constants and optimized average filter. Using one signal ADC sample, τ_1=59 µs and τ_2=60 µs has the best SNR at 25.7, a 36% increase over τ_1=15 µs and τ_2=15 µs at 18.9. This result shows the benefit of optimizing the amplifier time constants. When multiple samples are averaged, the SNR improves further. Averaging 5 samples 20 µs apart starting at 48 µs after the LED is enabled brings the SNR at 1 nA up to 31.1 when τ_1=15 µs and τ_2=15 µs.



t_{LED}=100 µs t_{SAMP}=20 µs

Figure 4-11. SNR at 1 nA with Varying Amplifier Speeds

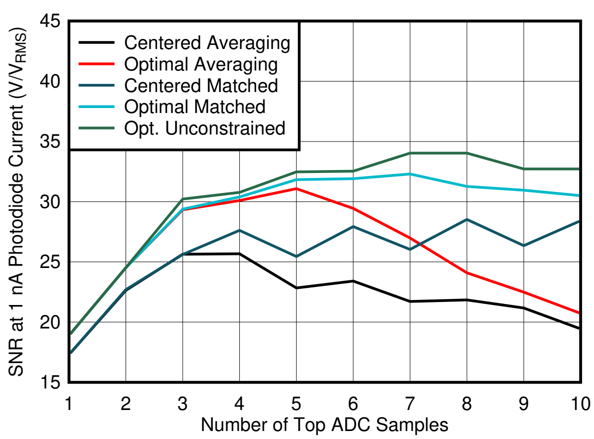


t_{LED}=100 µs t_{SAMP}=20 µs

Figure 4-12. Optimal First Top ADC Sample for Each Amplifier Speed

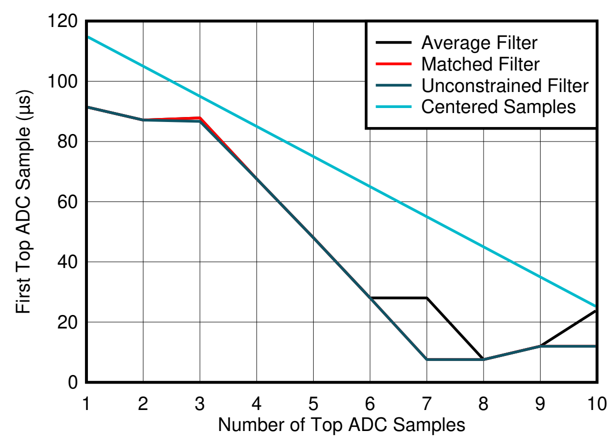
4.3.2 Varying Digital Filter and ADC Timing

Optimizing the filter by changing the timing of the samples further improves the SNR. Using τ_1=15 µs and τ_2=15 µs, the SNR at 1 nA for averaging 5 samples improves from 22.8 to 31.1 by taking the first ADC sample at 48 µs instead of 75 µs. The optimized matched filter with 7 ADC samples has an SNR/nA of 32.3. The unconstrained filter has the best SNR of the three filter types, 34.0, achieved with 7 and 8 ADC samples.



t_{LED}=100 µs t_{SAMP}=20 µs τ_1=15 µs τ_2=15 µs

Figure 4-13. SNR at 1 nA with Varying Digital Filter and ADC Timing



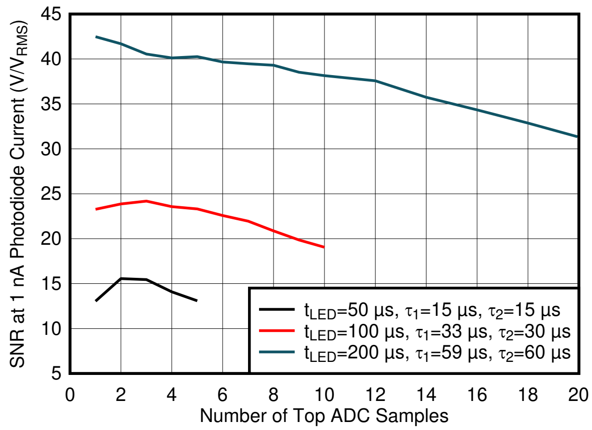
t_{LED}=100 µs t_{SAMP}=20 µs τ_1=15 µs τ_2=15 µs

Figure 4-14. Optimal First Signal Sample for Each Digital Filter

4.3.3 Varying LED Pulse Length

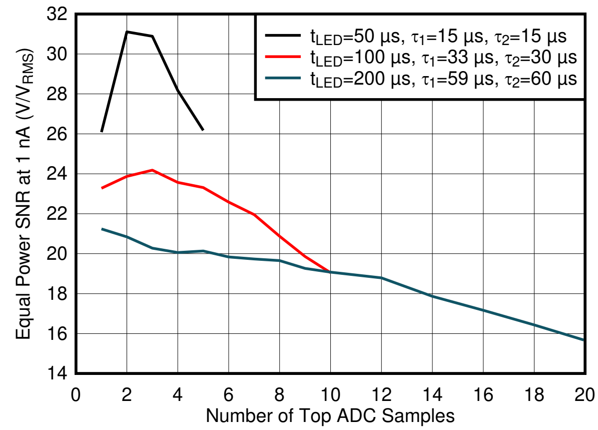
Varying the LED pulse length t_{LED} has a significant effect on the SNR. When scaling t_{LED}, τ_1 and τ_2 by two, the SNR is expected to improve by the square root of two. With one ADC sample, the SNR/nA increases from

13.0 to 23.3 to 42.5 when t_{LED} is increased from 50 µs to 100 µs to 200 µs. However, this also increases the power consumption, since the LED is enabled for more time. If the LED current is scaled to keep the power consumption constant, assuming that the photodiode current increases proportionally to the LED current and the LED supply voltage is constant, the 50 µs pulse has the highest SNR as shown in Figure 4-16. In general, increasing the LED pulse length and amplifier time constants is an effective way to increase the SNR when power consumption is flexible.



t_{SAMP}=20 µs

Figure 4-15. SNR at 1 nA Using Optimal Averaging Filter Varying LED Pulse Width

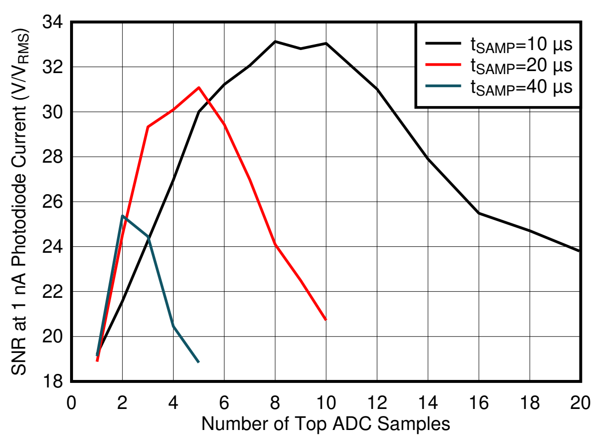


t_{SAMP}=20 µs

Figure 4-16. SNR at 1nA Using Optimal Averaging Filter Varying LED Pulse Width and LED Current

4.3.4 Varying ADC Sample Rate

The ADC sample rate is determined by the microcontroller, clock speeds, and sample and hold times. While there may not be much adjustability of the ADC sample rate in a system, it is important to consider the effects of sample rate on the SNR. Three ADC sample rates are used to calculate the SNR, shown in Figure 4-17. Decreasing the ADC sampling interval from 40 µs to 20 µs to 10 µs increases the maximum attainable SNR from 25.4 to 31.1 to 33.1. The benefit of taking multiple top ADC samples decreases as the ADC sampling interval increases. As the ADC sampling interval approaches the LED pulse width, reduce the number of top ADC samples and increase τ_1 and τ_2.

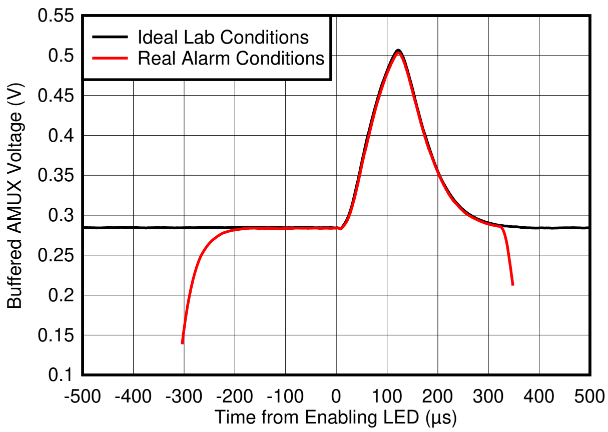


t_{LED}=100 µs τ_1=15 µs τ_2=15 µs

Figure 4-17. SNR at 1 nA with Optimal Averaging Filter Varying ADC Sample Interval

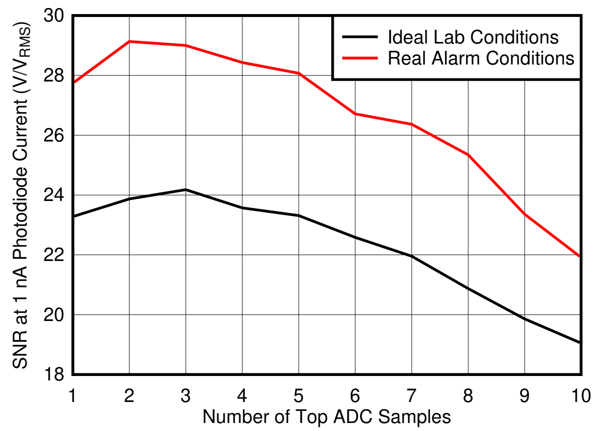
4.3.5 Real and Ideal System Conditions

SNR measurements taken using laboratory conditions is expected to provide a better SNR than in a real smoke alarm. For this reason, a set of measurements are taken using a 2V power supply, the TPS8802 boost converter, and a MSP430F5529 Launchpad microcontroller to control the TPS8802. The buffered AMUX output is measured using an oscilloscope. Figure 4-18 displays the 100 waveform average of each condition, showing that the pulse shape is nearly identical. The achieved SNR is higher using the real system, shown in Figure 4-19. No SNR disadvantage is observed from enabling and disabling the photo amplifier, AMUX, and boost converter as done in a smoke alarm.



t_{LED}=100 µs τ_1=30 µs τ_2=30 µs

Figure 4-18. Comparison of Noiseless Real and Ideal System Condition Pulse Shape

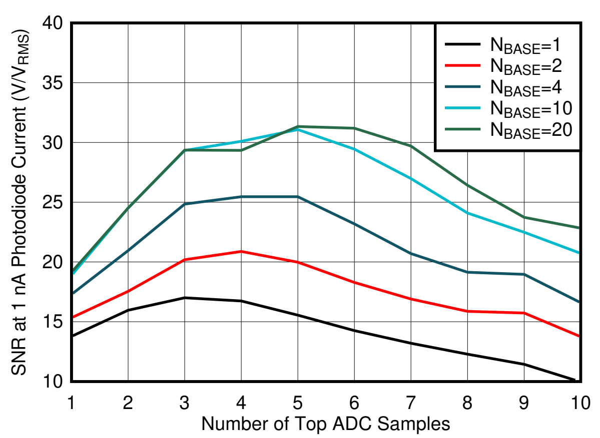


t_{LED}=100 µs τ_1=30 µs τ_2=30 µs

Figure 4-19. SNR at 1 nA for Real and Ideal System Conditions

4.3.6 Number of Base Samples

One of the simplest methods of improving SNR is to take multiple ADC samples of the base pulse level. The improvement is demonstrated in Figure 4-20. Increasing the number of base ADC samples from 1 to 20 improves the SNR at 1 nA from 13.8 to 19.1 when one signal ADC sample is taken. When five signal ADC samples are taken, the SNR at 1 nA improves from 15.6 to 31.3. A small amount of power consumption is required to keep the photo amplifier enabled and take the extra ADC samples, but this amount is insignificant compared to the LED power consumption.

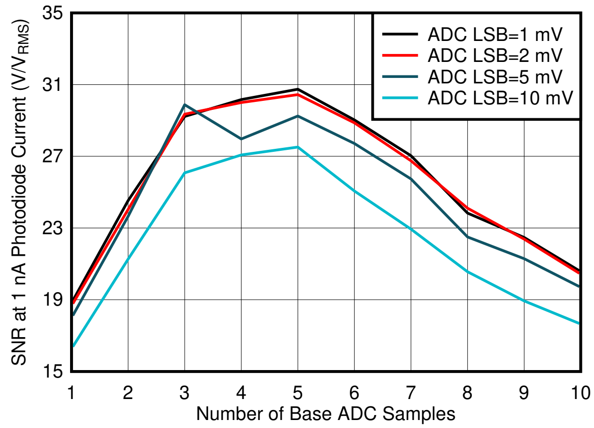


t_{LED}=100 µs τ_1=15 µs τ_2=15 µs

Figure 4-20. SNR at 1 nA With Varying Number of Base ADC Samples

4.3.7 ADC Resolution

The ADC resolution can have an effect on the SNR if it is too low. ADC LSB sizes of 1 mV, 2 mV, 5 mV, and 10 mV are simulated by rounding the waveform to the nearest LSB in MATLAB. The SNR starts to drop when the LSB size is 5 mV or above. If the LSB size is greater than the noise or signal level, increase the photo amplifier gain using the R_{PH} resistor or programmable gain stage.



t_{LED}=100 µs τ_1=15 µs τ_2=15 µs

Figure 4-21. SNR at 1 nA With Varying ADC LSB Size

5 Summary

By modifying amplifier speed and gain, LED current and pulse width, multiple ADC sample timing, and digital processing, the TPS880x achieves high SNR (>30 dB) with 1 nA photodiode current. Measurements of a photoelectric smoke sensor with a TPS8802EVM demonstrate various methods of improving SNR. A model of the system signal and noise provides intuition behind the results. The most effective methods are optimizing the amplifier time constants and taking multiple ADC samples. Longer time constants are effective when one top ADC sample is taken and shorter time constants are effective when multiple top ADC samples are taken. The optimal number of samples depends on the ADC sample rate, LED pulse length, and type of digital filtering. The averaging filter is sufficient for most applications and can be changed to a matched filter for higher SNR at the cost of more computational complexity. In power-critical applications, shortening the LED pulse width and increasing LED current can improve the SNR. The TPS880x smoke alarm AFE using these methods enables the next generation of smoke alarms to achieve fewer false alarms, reduced power consumption, and lower system cost.

6 References

- *Noise Analysis for High Speed Op Amps*
- *Noise Analysis In Operational Amplifier Circuits*
- *Stability Analysis Of Voltage-Feedback Op Amps, Including Compensation Technique*