Analyzing and calculating noise bandwidth in ADC systems – the digital filter

TIPL xxxx

TI Precision Labs – ADCs

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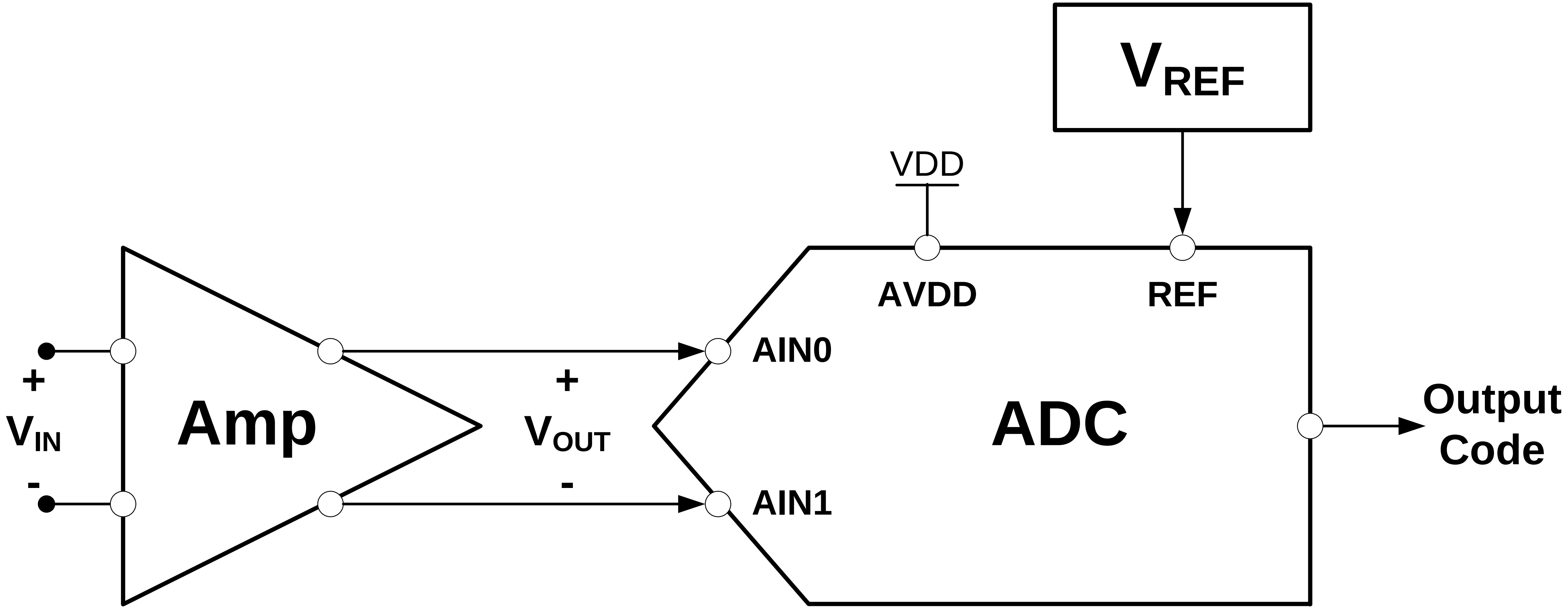
Presented by Alex Smith

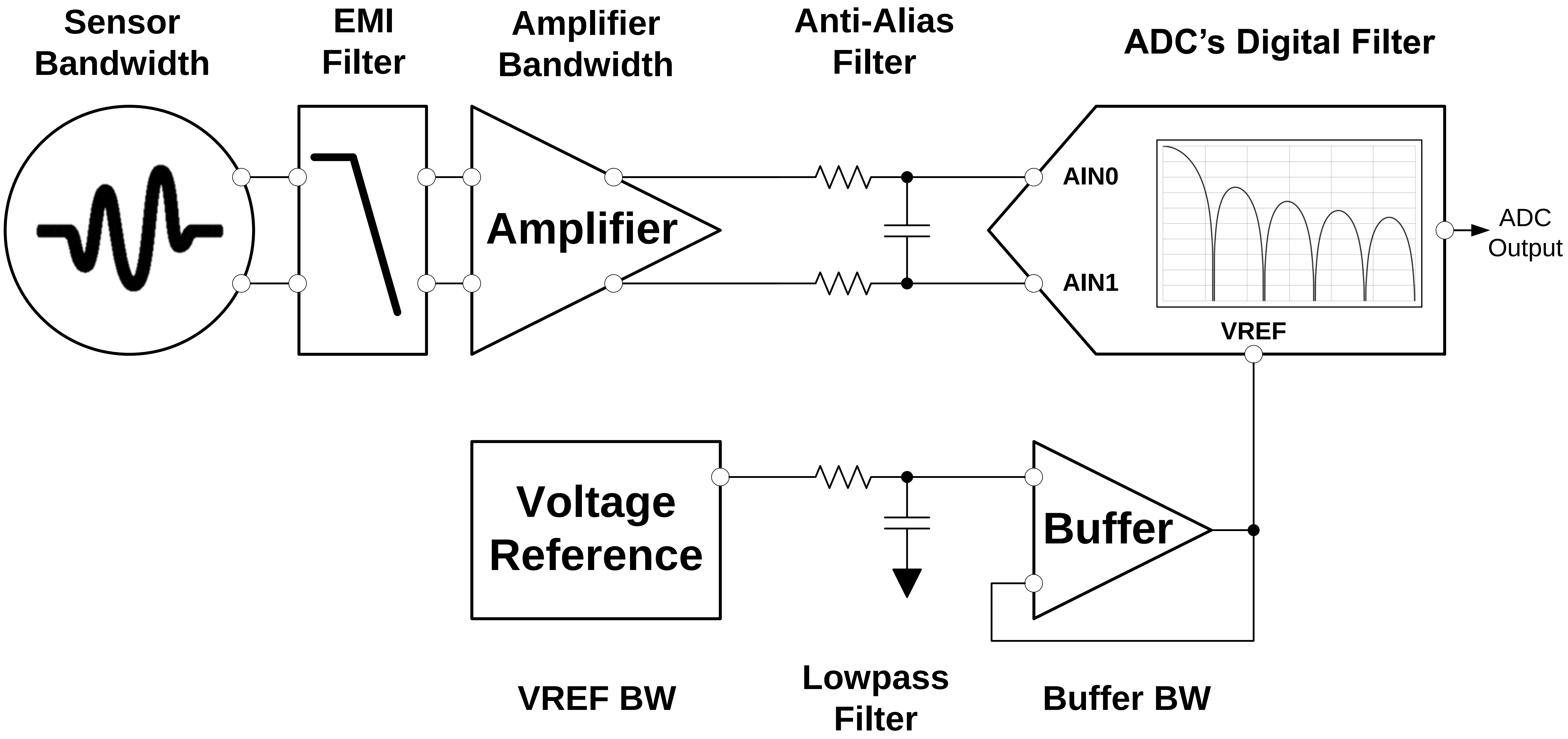
Basic data acquisition system noise calculation



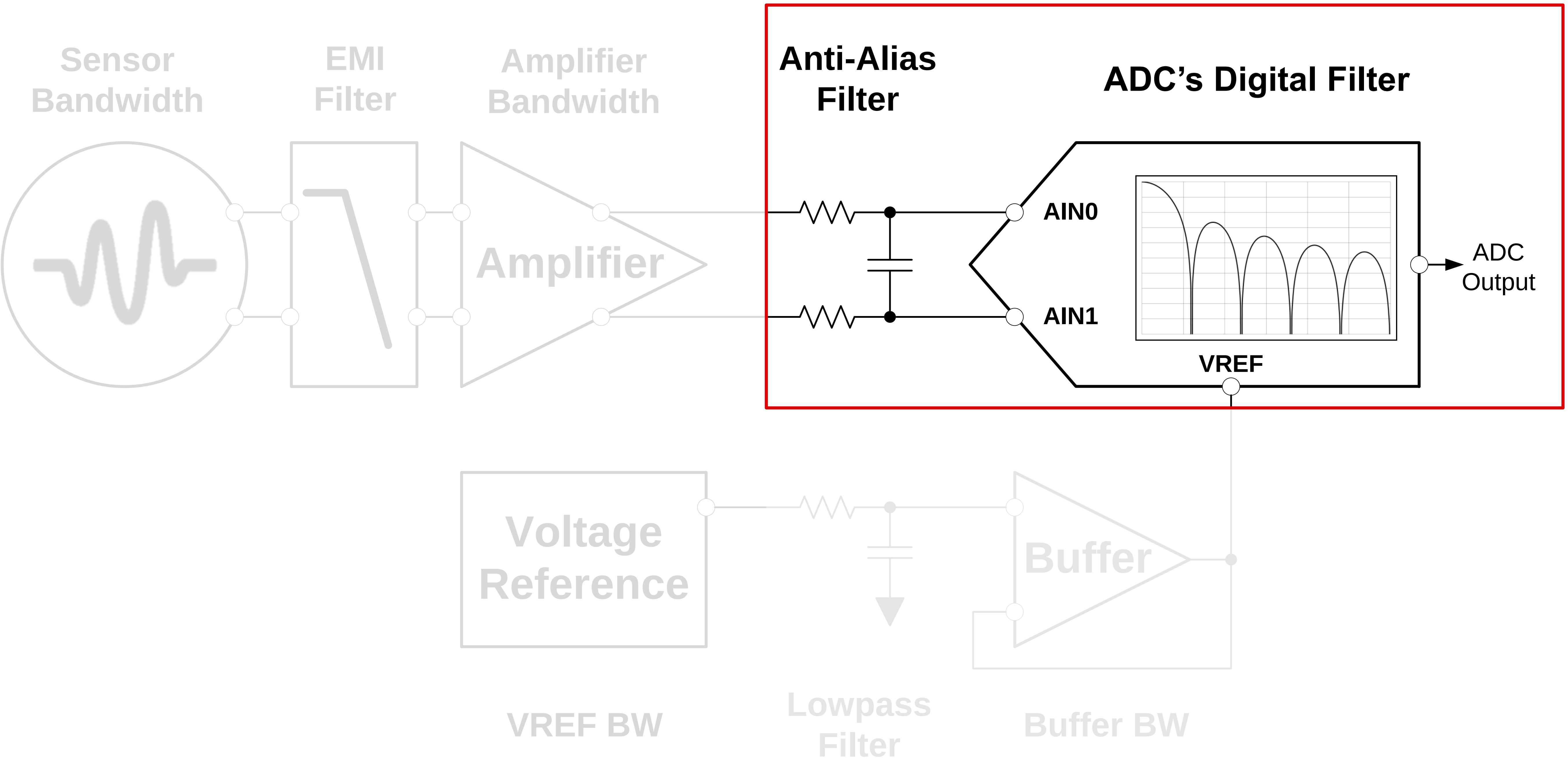
$$V_{N,Total} = \sqrt{V_{N,AMP}{}^2 + V_{N,ADC}{}^2 + V_{N,REF}{}^2}$$

$$ex.\ V_{N,AMP} = V_{Noise\ Density\ (NSD)} * \sqrt{Bandwidth}, \qquad V_{NSD} = \frac{V_{Noise}}{\sqrt{Hz}}$$

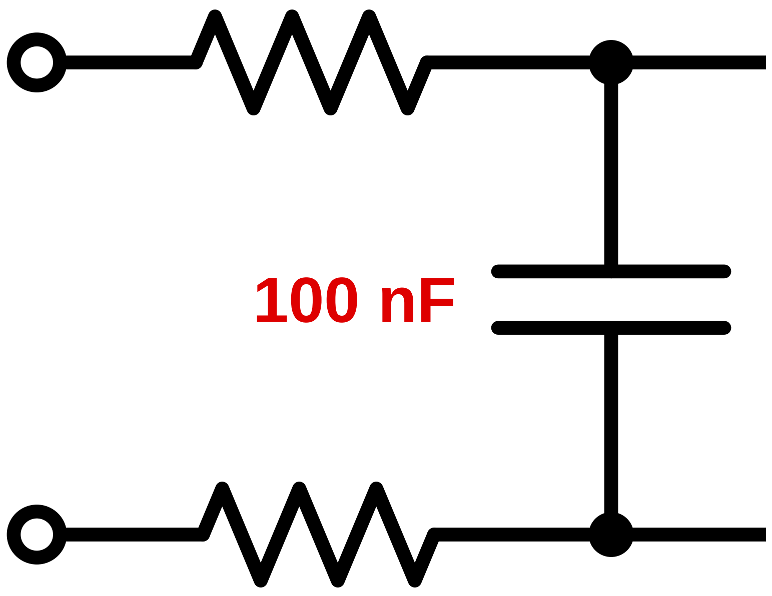
Filtering in a typical signal chain



What this presentation analyzes



Anti-aliasing filter effective noise bandwidth

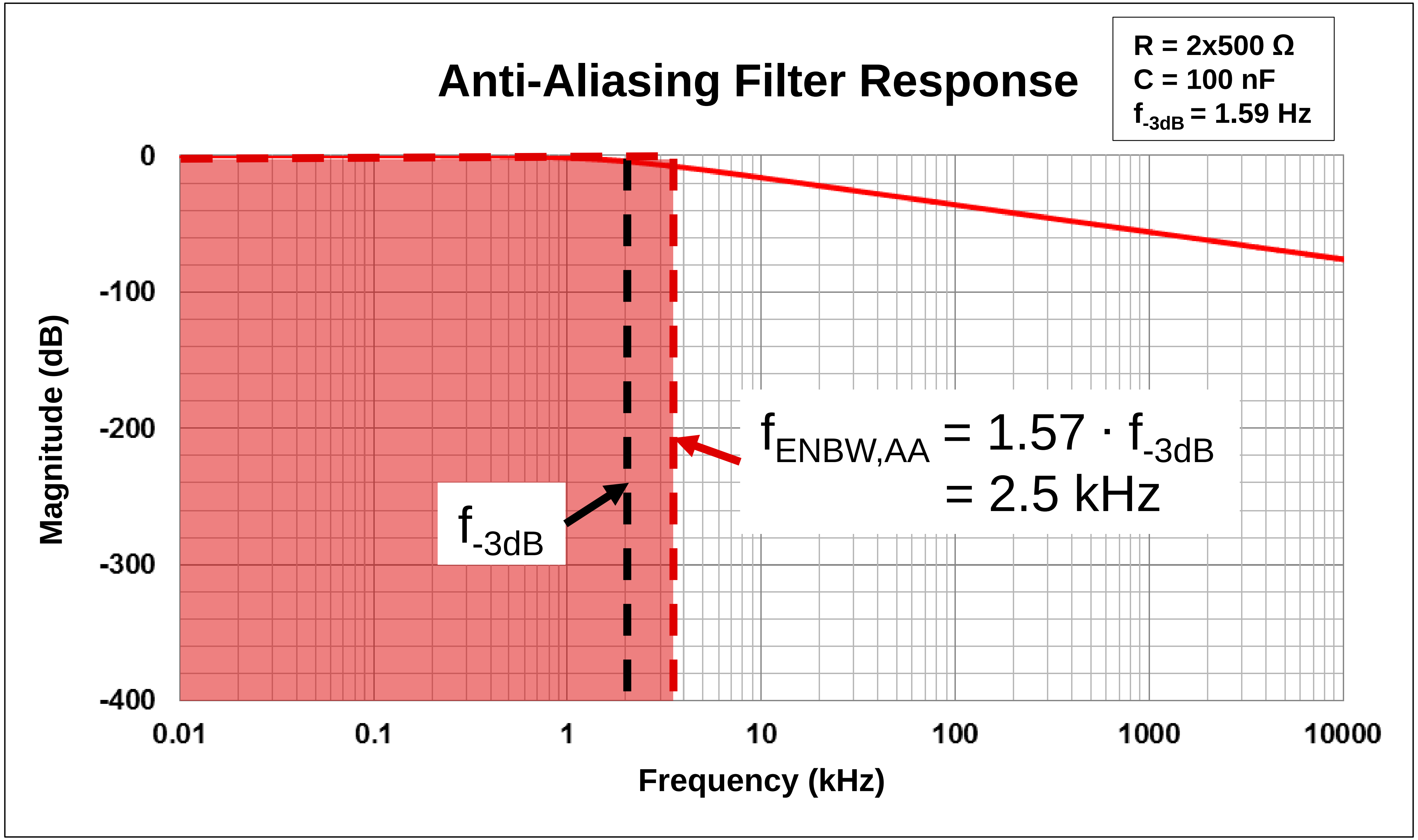


$$f_{-3dB} = \frac{1}{2\pi \cdot (2R) \cdot C}$$

$$f_{ENBW} = 1.57 \cdot f_{-3\mathrm{dB}}$$

Anti-Alias (RC) Filter	
-3 dB Cutoff (f_{-3dB}) (kHz)	1.59
Noise Bandwidth (f_{ENBW}) (kHz)	2.5

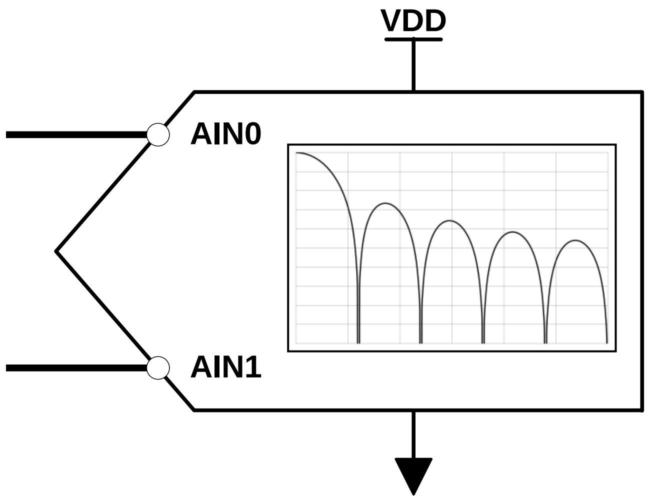
Anti-aliasing filter frequency response

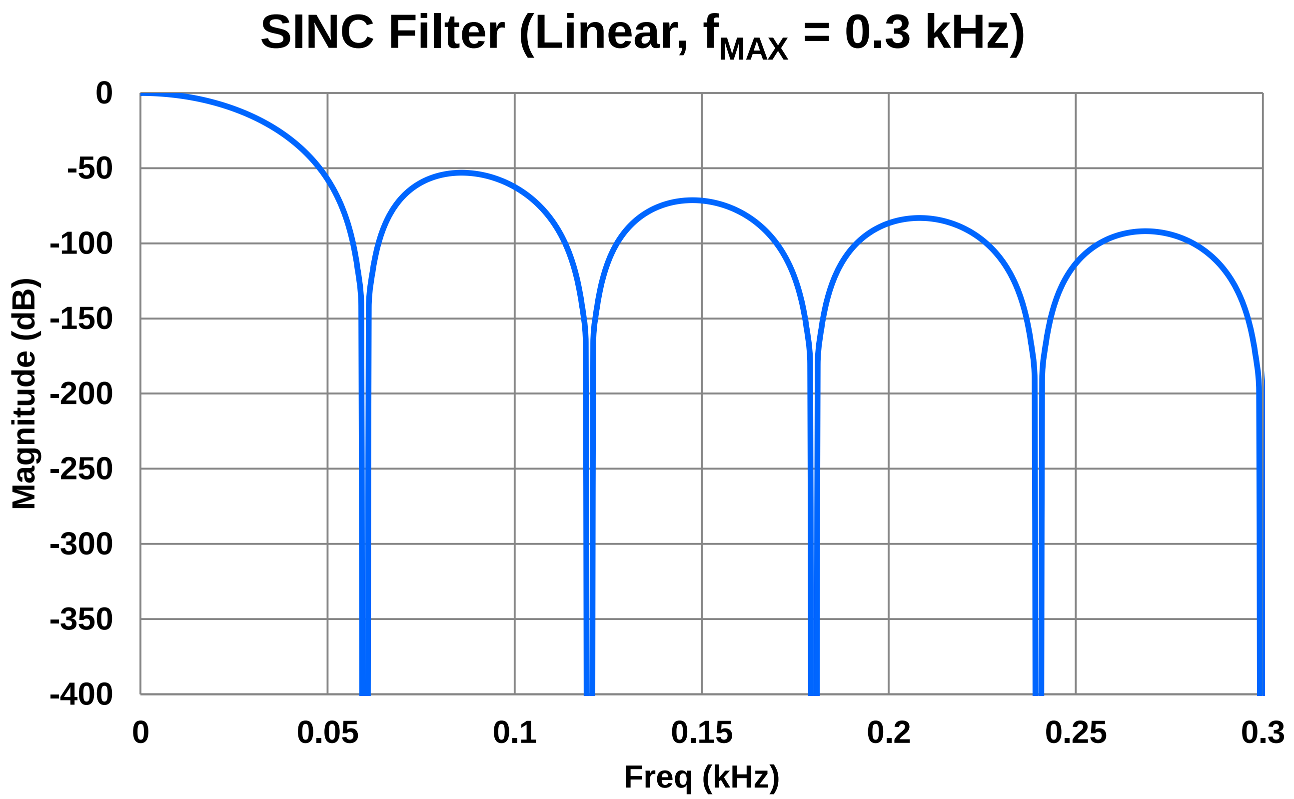


Digital filter effective noise bandwidth

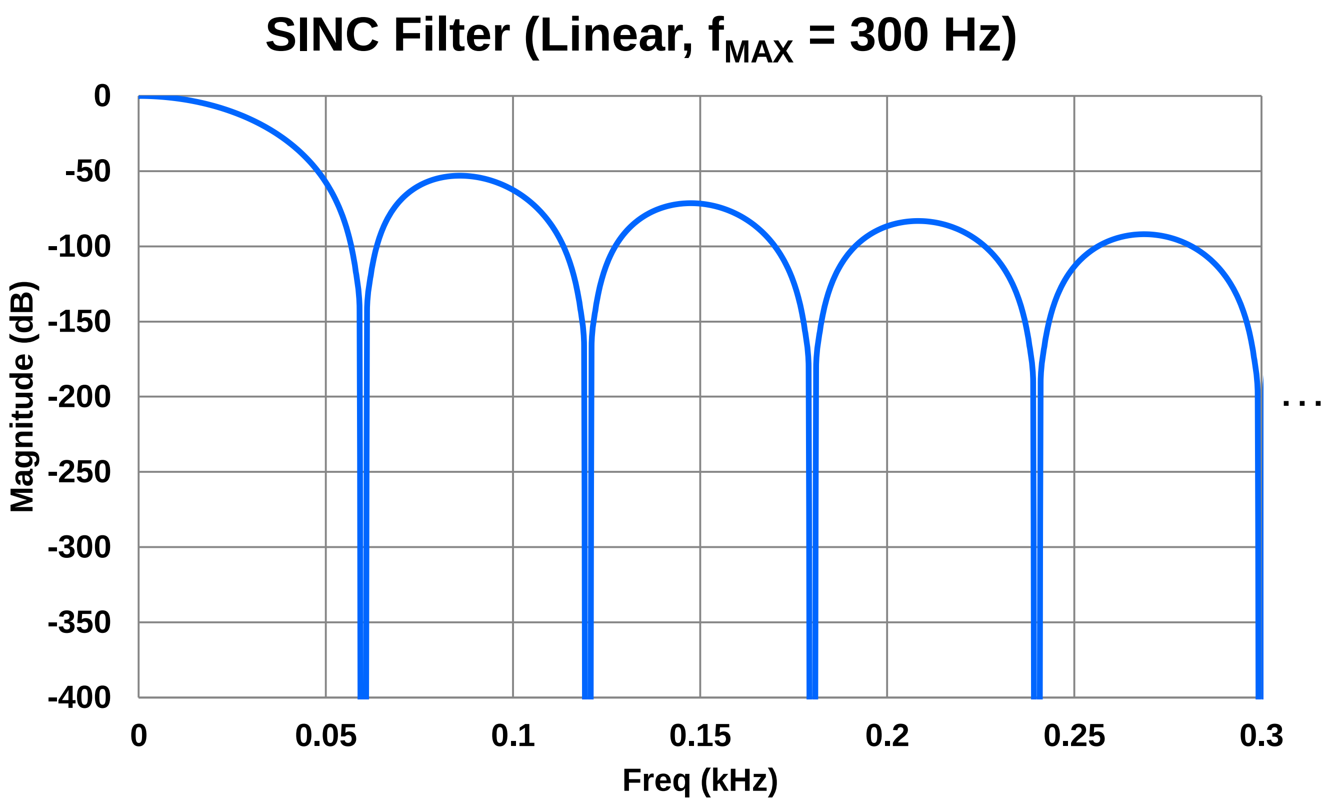
ADS1261's SINC Filter	
Data Rate (SPS)	60
SINC Filter Order	4
-3dB Cutoff Frequency (Hz)	13
ENBW (Hz)	?

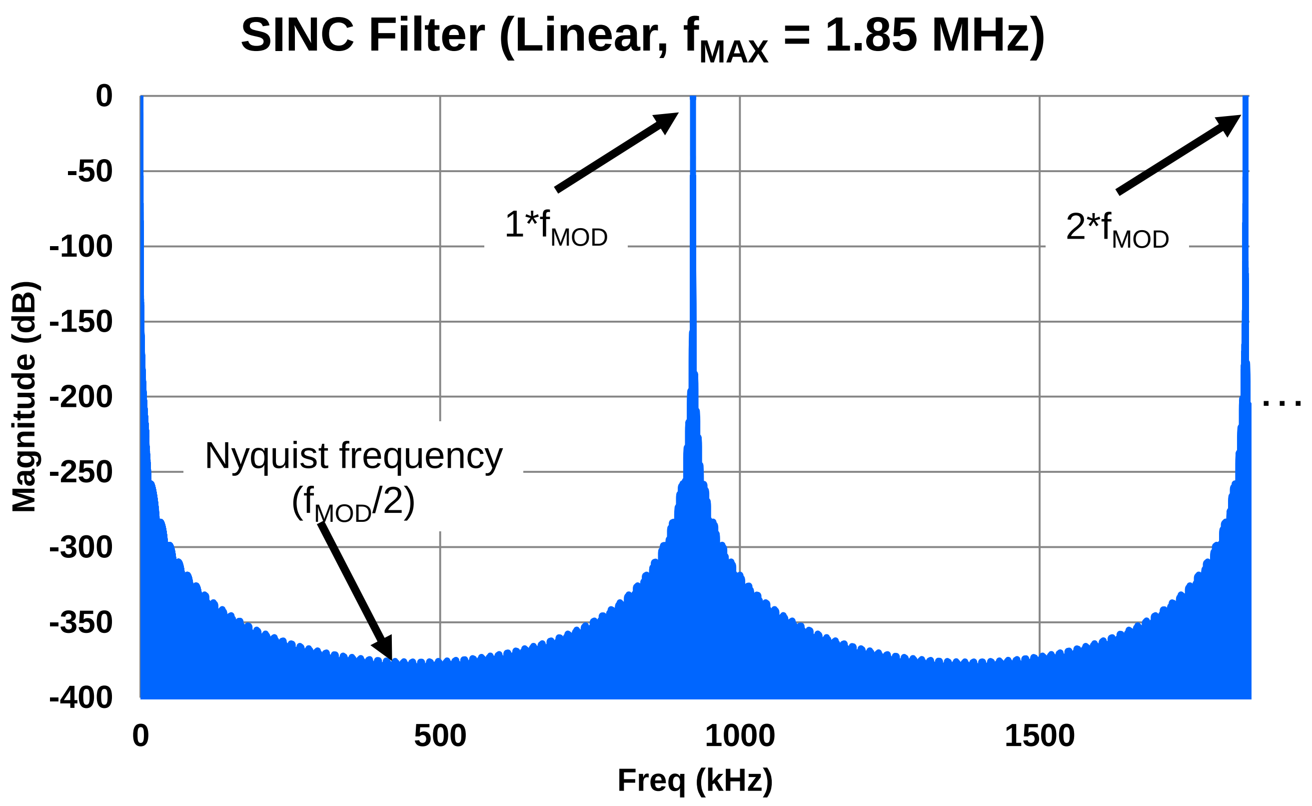
ADS1261





Changing f_{MAX} on sinc filter plots

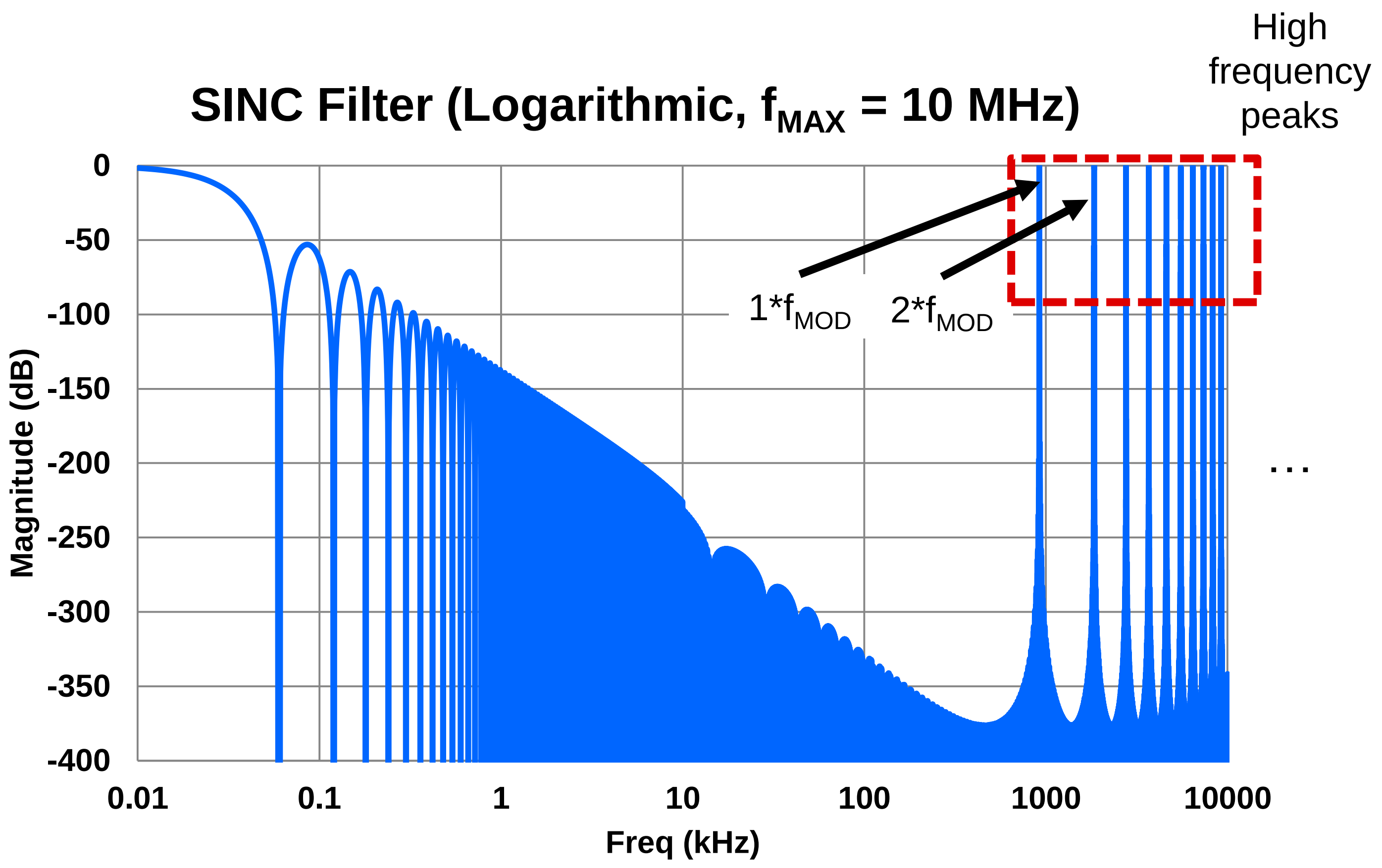


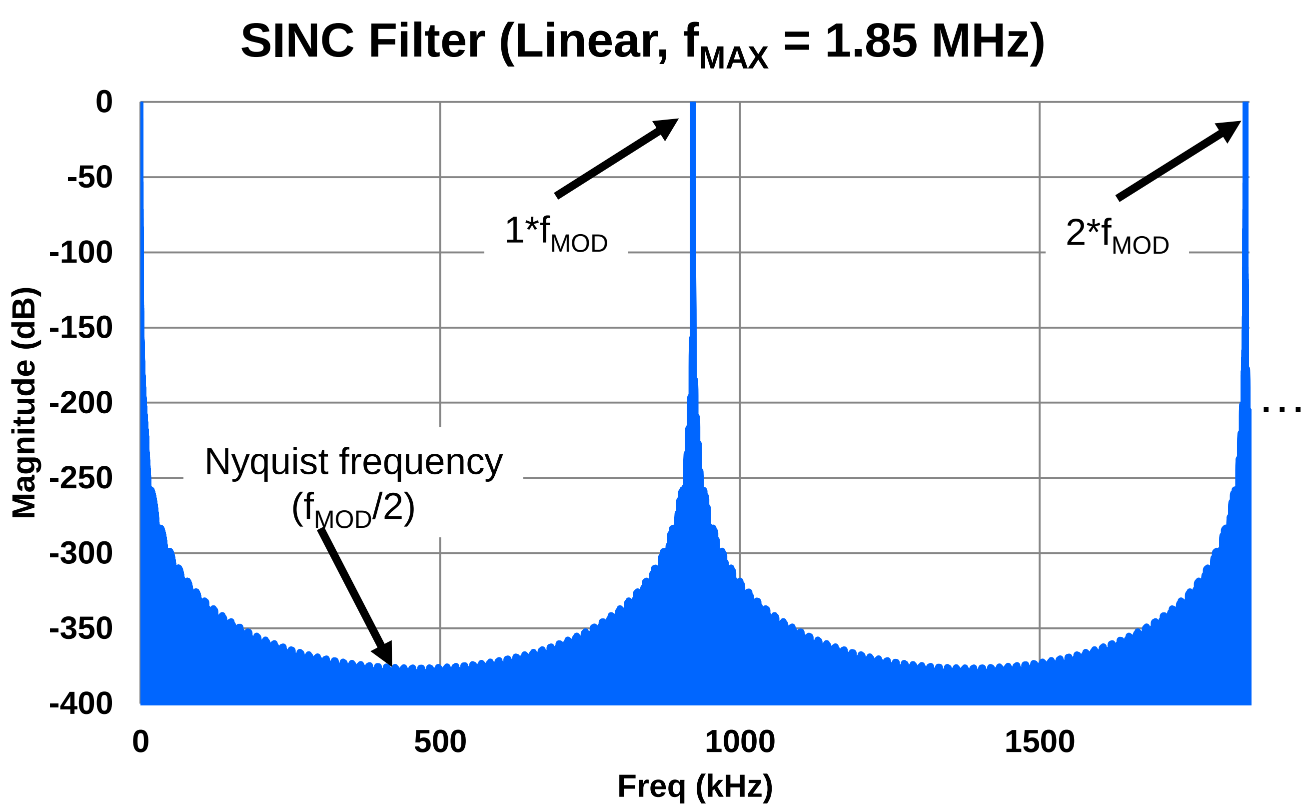


$$f_{MOD,ADS1261} = \frac{f_{\mathrm{CLK}}}{8}$$

$$f_{MOD,ADS1261} = \frac{7.3728\ MHz}{8} = 921.6\ kHz$$

Linear vs logarithmic frequency axis





Integration Limits	f_{ENBW} (Hz)
n/a	∞
1*f_{MOD}	42
2*f_{MOD}	70
10*f_{MOD}	282

$$f_{MOD,ADS1261} = \frac{f_{CLK}}{8}$$

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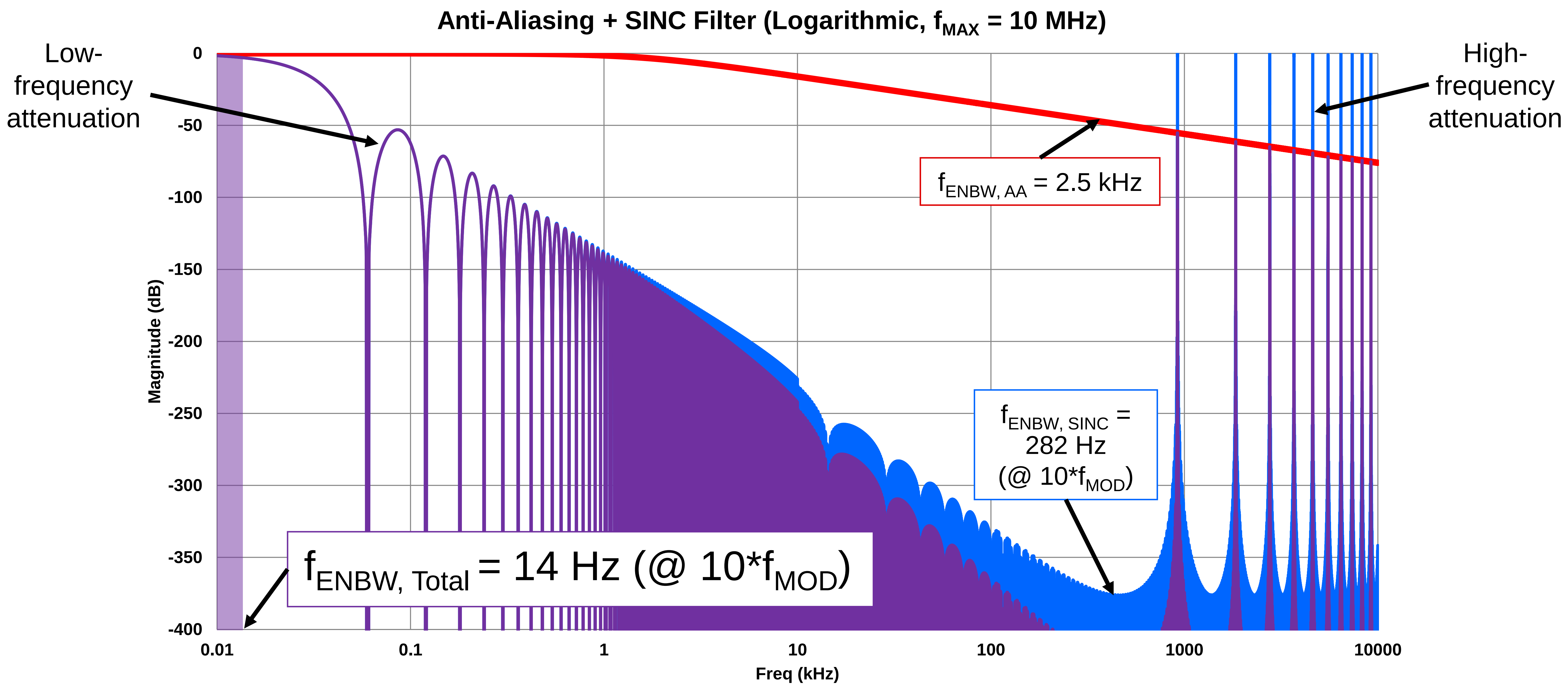
Combined filter frequency response



Approximations for the combined noise bandwidth

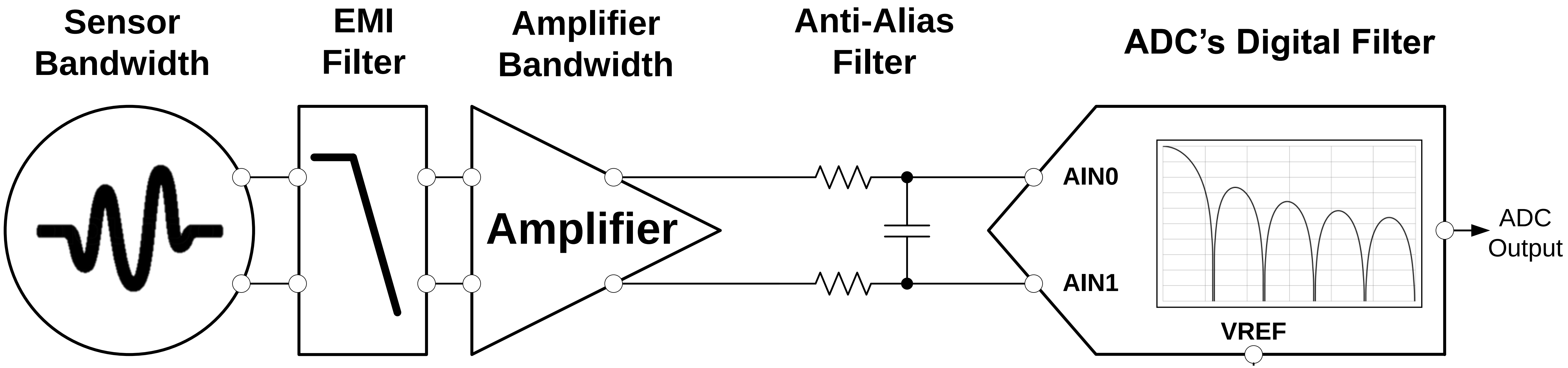
ADS1261		System ENBW (Hz)			
Data Rate (SPS)	$f_{C,Digital}$ (Hz)	AA Filter (f_c = 25 Hz)	AA Filter (f_c = 250 Hz)	AA Filter (f_c = 2,500 Hz)	AA Filter (f_c = 25,000 Hz)
2.5	0.58	**0.59**	**0.59**	**0.59**	**0.59**
5	1.15	**1.19**	**1.19**	**1.19**	**1.19**
10	2.28	**2.37**	**2.39**	**2.39**	**2.39**
16.7	3.80	**3.92**	**3.98**	**3.99**	**4.31**
20	4.63	**4.68**	**4.78**	**4.78**	**4.79**
50	11	**10.72**	**11.96**	**11.97**	**12.09**
60	13	**12.40**	**14.34**	**14.37**	**14.40**
100	22	**17.69**	**23.82**	**23.96**	**24.10**
400	90	**30.87**	**88.83**	**95.77**	**96.16**
1,200	272	**36.10**	196.79	**285.11**	**288.13**
2,400	543	**37.62**	267.42	**556.39**	**574.60**
4,800	1,076	**38.42**	319.89	1026.41	**1137.07**
7,200	1,580	**38.69**	340.86	1392.37	**1676.52**
14,400	2,930	**38.95**	**363.18**	2048.71	**3077.72**
19,200	3,900	**39.03**	**370.23**	2353.61	**4076.05**

If $f_{C,digital} \leq f_{C,AA}$, then
$\mathbf{f_{ENBW,Total} \approx f_{C,digital}}$

If $f_{C,digital} \geq 10 {*} f_{C,AA}$, then
$\mathbf{f_{ENBW,Total} \approx f_{ENBW,AA}}$

Otherwise, **no approximation exists**
→ use integration OR
smallest: $f_{C,\ Digital}$ or $f_{ENBW,AA}$

System noise bandwidth



$$V_{N,Total} = \sqrt{\left(V_{NSD,Sensor} * \sqrt{BW_{Sensor}}\right)^2 + \left(V_{NSD,EMI} * \sqrt{BW_{EMI}}\right)^2 + \left(V_{NSD,AMP} * \sqrt{BW_{AMP}}\right)^2 + \left(V_{NSD,AA} * \sqrt{BW_{AA}}\right)^2 + \left(V_{NSD,ADC} * \sqrt{BW_{ADC}}\right)^2}$$

$$if\ BW_{Sensor}, BW_{EMI}, BW_{AMP}, BW_{AA} \geq 10 * BW_{ADC}, then:$$

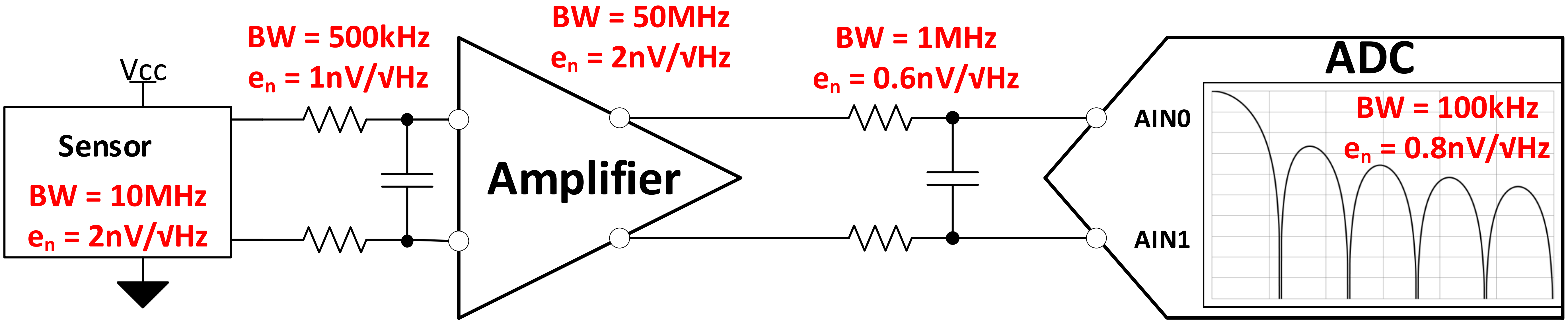
System noise bandwidth

$$V_{N,Total\ (SNBW)} = \sqrt{\left[\left(V_{NSD,Sensor}\right)^2 + \left(V_{NSD,EMI}\right)^2 + \left(V_{NSD,AMP}\right)^2 + \left(V_{NSD,AA}\right)^2 + \left(V_{NSD,ADC}\right)^2\right] * \boldsymbol{BW_{ADC}}}$$

Thanks for your time!
Please try the quiz.

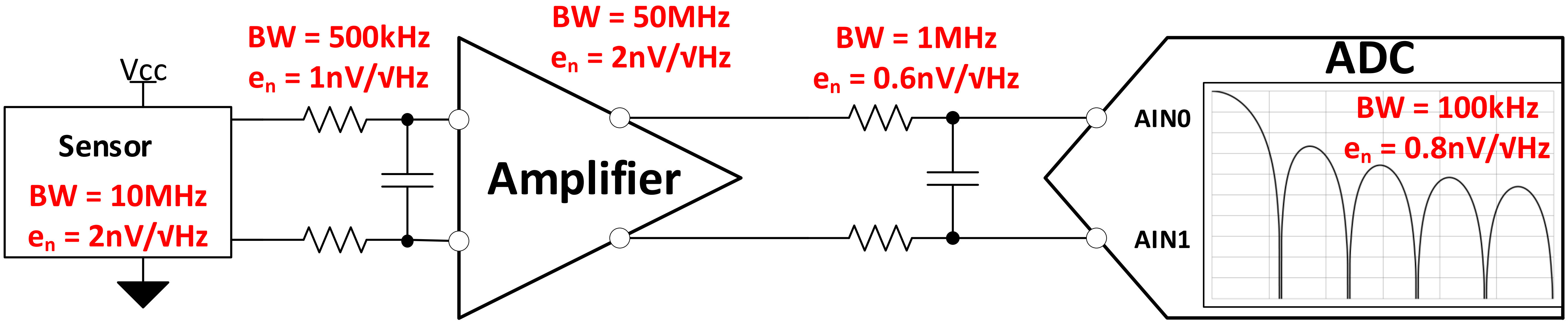
Quiz: Noise bandwidth including digital filters

1. What is the cutoff frequency for the system below? What is the noise bandwidth?
   a) 100kHz, 100kHz
   b) 100kHz, 157kHz
   c) 1MHz, 1.57MHz
   d) 10MHz, 15.7MHz
   e) 50MHz, 78.5MHz



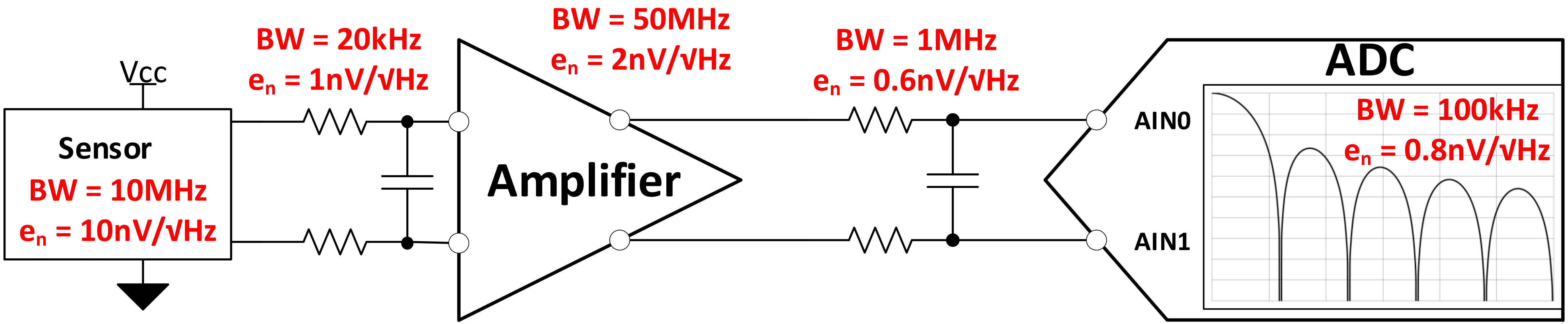
Quiz: Noise bandwidth including digital filters

2. Use the circuit from the previous problem. What is the total noise for the system below?
   a) 570nV rms
   b) 1µV rms
   c) 1.25µV rms
   d) 3.45µV rms
   e) 4.85µV rms



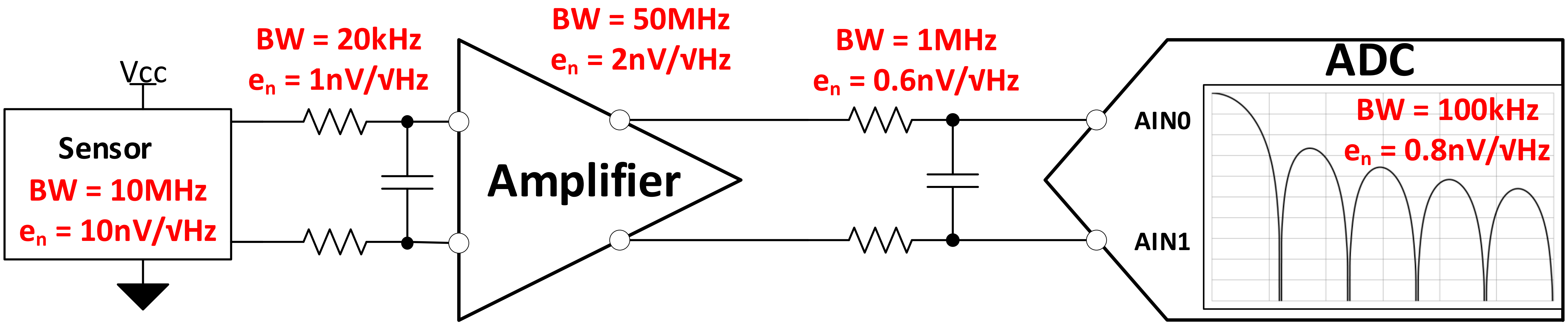
Quiz: Noise bandwidth including digital filters

3. What is the effective -3dB bandwidth seen by the sensor below?
   a) 10MHz
   b) 20kHz
   c) 50MHz
   d) 1MHz
   e) 100kHz



Quiz: Noise bandwidth including digital filters

4. What is the effective -3dB bandwidth seen by the amplifier in this circuit?
   a) 50MHz
   b) 1MHz
   c) 100kHz



Quiz: Noise bandwidth including digital filters

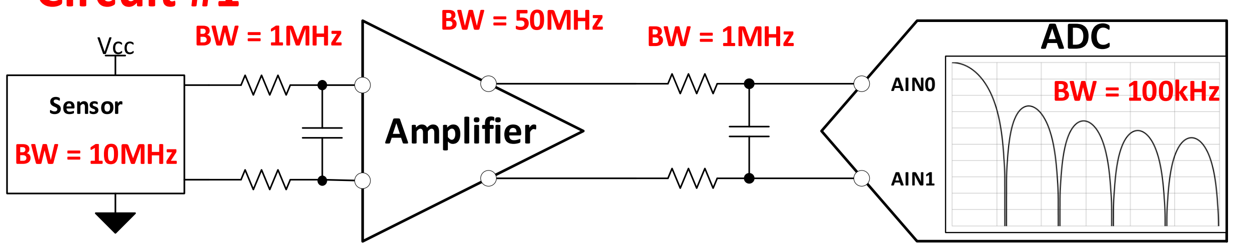
5. Equation #1 is an approximation that can be used to calculate total noise for many different ADC systems. Which of the three systems below cannot be analyzed using this approximation?

   a) Circuit #1
   b) Circuit #2
   c) Circuit #3
   d) The approximation will work for all circuits

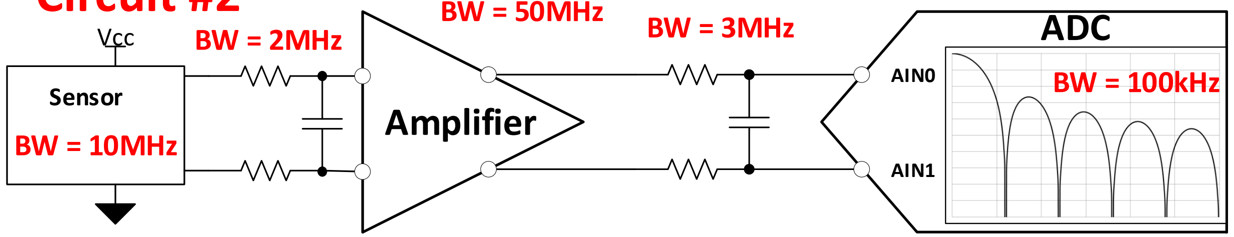
Equation #1

$$E_n = \left(\sqrt{(e_{nSensor})^2 + (e_{nRF\_filt})^2 + (e_{nAmp})^2 + (e_{nADCFilter})^2 + (e_{nDigFilt})^2}\right)\left(\sqrt{BW_n}\right)$$

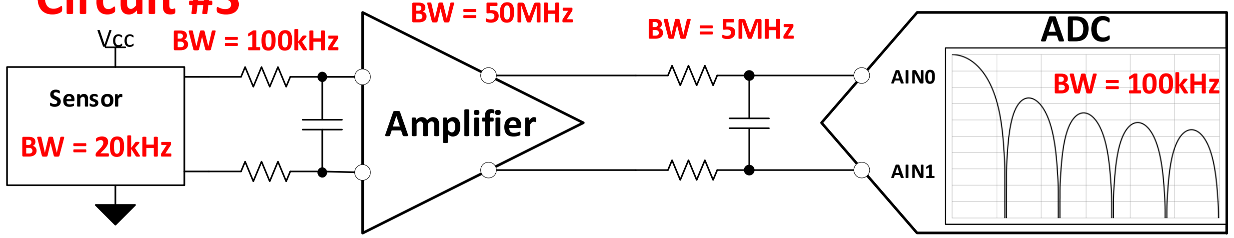
Circuit #1



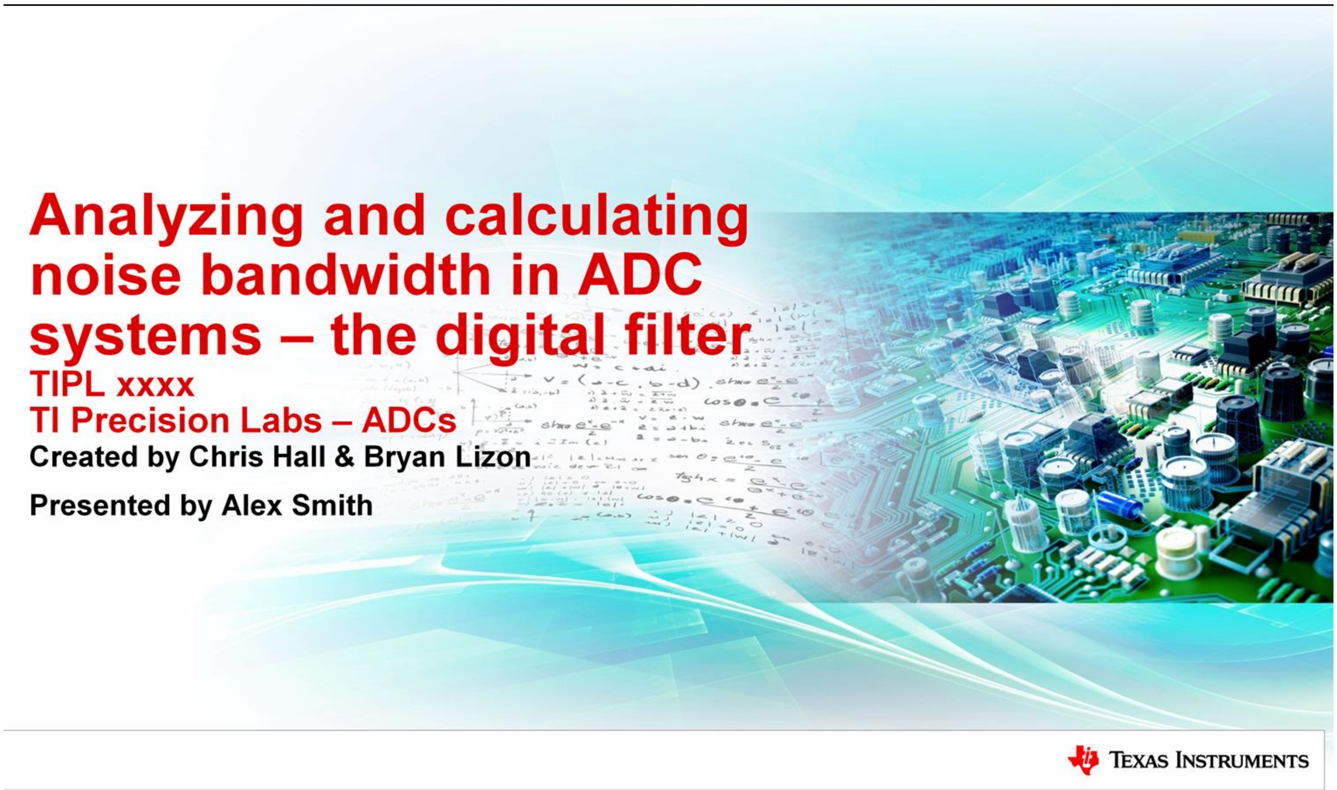
Circuit #2



Circuit #3



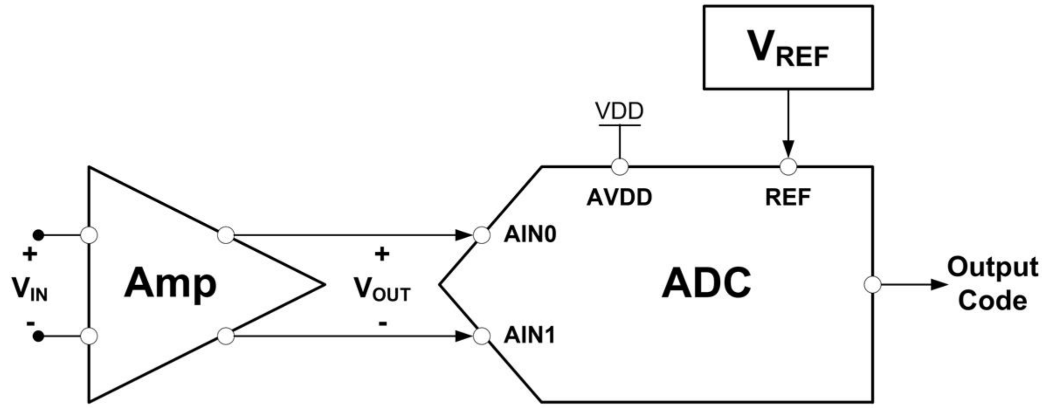
Thanks for your time!



Hello, and welcome to the TI Precision Labs module covering digital filter effective noise bandwidth in ADC systems. In a previous Precision Labs module, we discussed what effective noise bandwidth is as well as how to calculate and simulate it for multi-stage filter systems. In this module, we will analyze an ADC's digital filter frequency response and its combined affect with an anti-aliasing filter. Through a design example, we will identify approximations for the system noise bandwidth to simplify your analysis. You will also learn how a digital filter's bandwidth often acts as the limiting factor for the entire system. This allows you to calculate the total noise using one *system* bandwidth that is applicable to all components, instead of requiring you to determine each stage's unique bandwidth.

The goal for these effective noise bandwidth Precision Labs modules will be to apply the knowledge from these examples to help determine the total noise in your next signal chain design, regardless of the types of filtering you apply or the precision ADC you choose

Basic data acquisition system noise calculation



$$V_{N,Total} = \sqrt{{V_{N,AMP}}^2 + {V_{N,ADC}}^2 + {V_{N,REF}}^2}$$

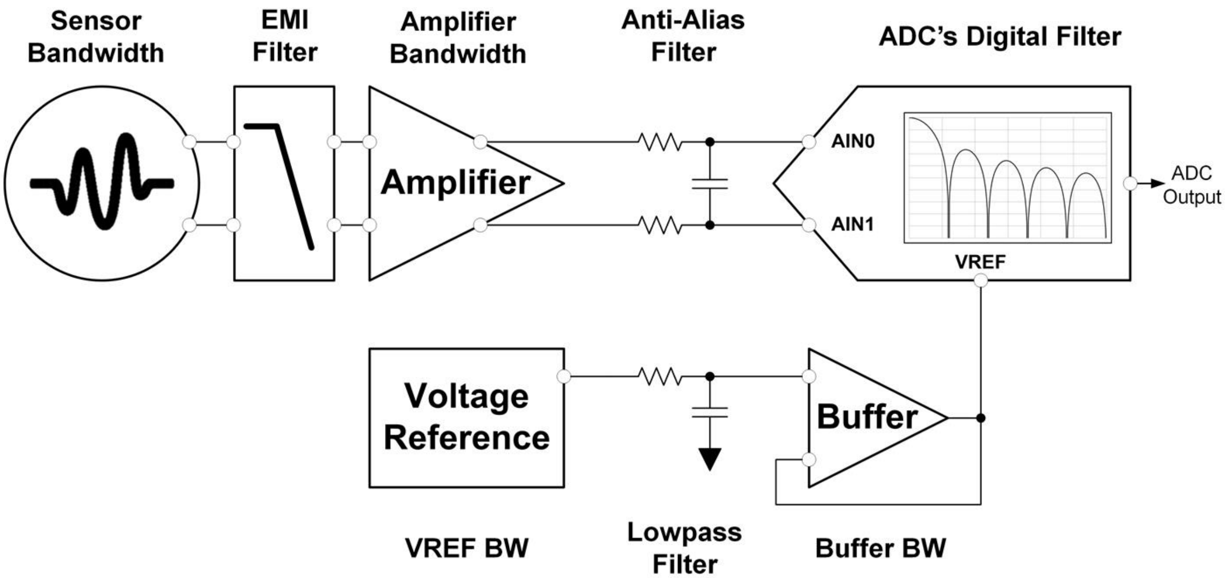
$$ex.\ V_{N,AMP} = V_{Noise\ Density\ (NSD)} * \sqrt{Bandwidth}, \qquad V_{NSD} = \frac{V_{Noise}}{\sqrt{Hz}}$$

Texas Instruments

To begin, let's revisit the simple data acquisition system analyzed throughout these Precision Lab ADC noise modules. In the previous presentation, it was discussed that you calculate this system's total noise by taking the root sum square of each component's noise contribution using the equation shown here for V,N,TOTAL. One of the challenges in calculating total system noise is that many components specify noise in different ways, including noise density. Noise density generalizes the relationship between noise power and frequency, instead of defining a noise value over a specific frequency range, and has the units of noise per root Hertz. In other cases, the component's noise values may be defined over a specific frequency range, though the bandwidth seen by that component *in your system*, as well as its noise contribution, might be different. In either case, you need to know the combined filtering and resulting bandwidth applied to each noise source to calculate total noise.

While that may seem simple for the block diagram shown here, determining the bandwidth seen by each component can be challenging if you account for all possible filtering sources

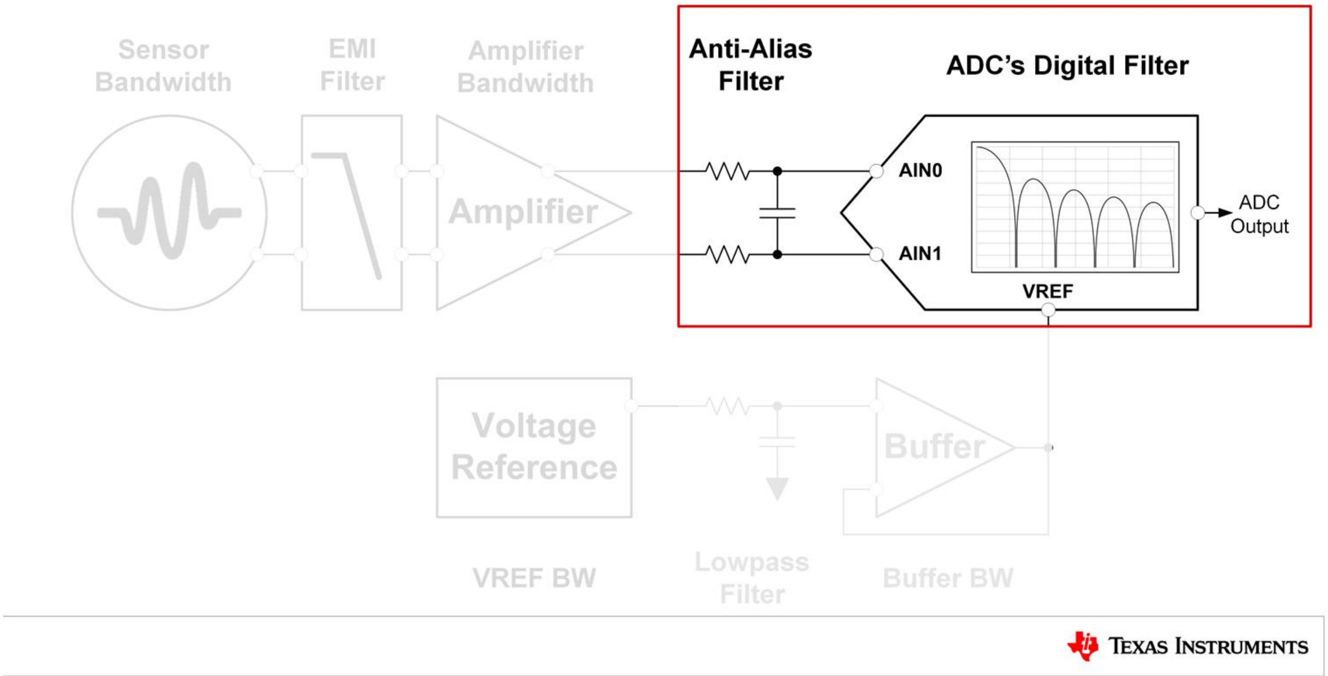
Filtering in a typical signal chain



For example, this more complete signal chain has many sources of filtering and two distinct input paths such that calculating bandwidth is not a trivial task. It is possible that the sensor's noise will be filtered differently compared to noise from the amplifier, or that the EMI filter noise component will differ from the anti-aliasing filter's, even though both are first-order lowpass filters. To determine the bandwidth and resulting noise for each component, you need to understand how to combine filters. You can review the precision Labs module on noise bandwidth for multi-stage filters for more information, as well as some approximations that can simplify your analysis. Additionally, please note that the information from that module will be used to support a design example in this presentation

Specifically, this presentation will focus on a commonly-used filter type that was not discussed in the previous module, the ADC's digital filter. This filter type is included in all delta-sigma and some SAR ADCs, so it is imperative to understand how the digital filter impacts the overall system for a complete understanding of signal chain noise analysis. Moreover, digital filters present unique challenges and behaviors compared to simple RC filters, requiring more detailed discussion. Finally, the digital filter tends to dominate the overall system bandwidth in many applications, enabling useful approximations similar to those derived in the previous module.

What this presentation analyzes

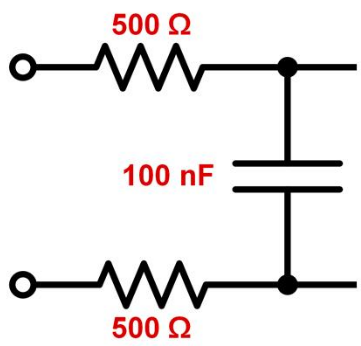


Therefore, this presentation will analyze the combined effect of the anti-aliasing filter and the ADC's digital filter. This makes sense since using an ADC with a digital filter requires an anti-aliasing filter for best performance. Moreover, the anti-aliasing filter cutoff frequency should be chosen relative to the ADC's sampling frequency or modulator clock, which will be discussed in more detail later in this presentation. As a result, these two components tend to dominate the overall system noise bandwidth in many applications, thereby determining the amount of noise that's able to pass into the system.

To better understand the combined affect these filters have, we will first calculate and compare the noise bandwidths of each filtering source separately. Then, we will discuss how to combine these filtering sources into one system effective noise bandwidth and compare this to the individual bandwidths of each component. Finally, we'll identify any useful approximations that may result from this analysis.

To begin the example, let's start by looking at the bandwidth of the anti-aliasing filter

Anti-aliasing filter effective noise bandwidth



$$f_{-3dB} = \frac{1}{2\pi \cdot (2R) \cdot C}$$

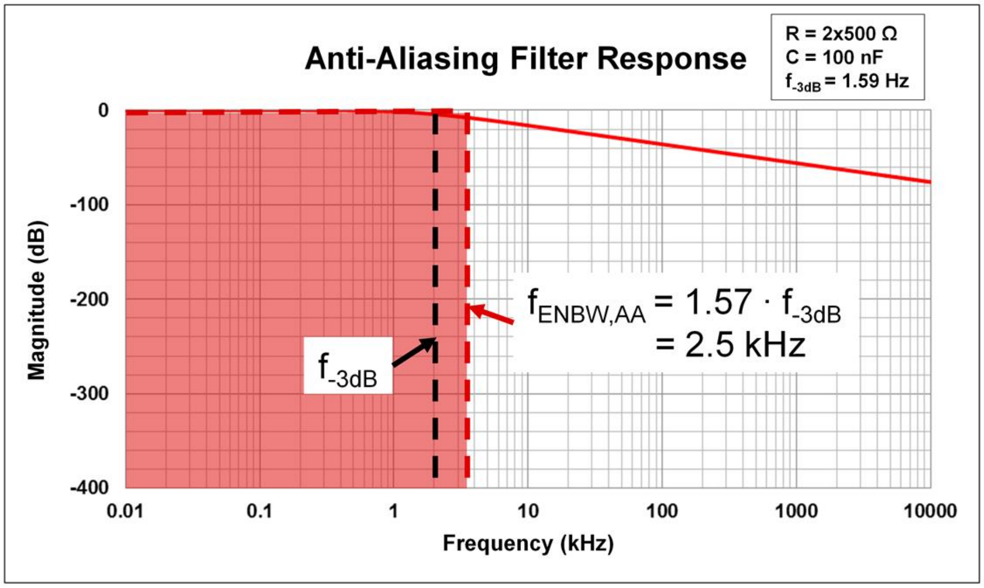
$$f_{ENBW} = 1.57 \cdot f_{-3\mathrm{dB}}$$

Anti-Alias (RC) Filter	
-3 dB Cutoff (f_{-3dB}) (kHz)	1.59
Noise Bandwidth (f_{ENBW}) (kHz)	2.5

The anti-aliasing filter for the ADC is a simple RC filter, so you can use the equations from the previous module to determine its cutoff and effective noise bandwidths. These equations are shown on the right. For this example, typical resistor and capacitor values were chosen, though other choices are acceptable. Take care when choosing components as using large component values to reduce the filter's noise bandwidth may cause unwanted issues.

For example, increasing the filter capacitor from 100 nF to 100 μF reduces the filter's effective noise bandwidth by a factor of 1000, but also increases the settling time by the same factor due to a larger RC time constant. Moreover, larger input resistors can lead to high leakage currents that result in less accurate measurements. Larger resistors will also add more noise to the circuit, which may not be acceptable given your system requirements.

Anti-aliasing filter frequency response



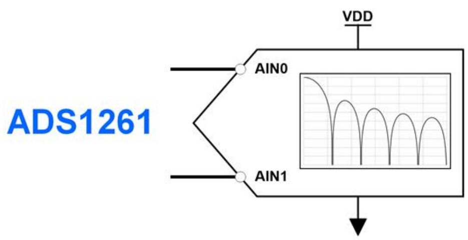
In the frequency domain, the anti-aliasing filter response looks like a typical low-pass filter, with its 3dB cutoff frequency denoted by the black dotted line.

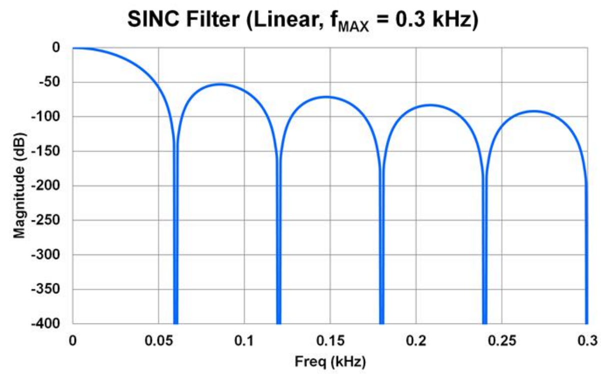
From the calculations and table on the previous slide, this filter's noise bandwidth is 2.5 kHz and is represented by the red brickwall filter shown here. As the previous module on multi-stage filters demonstrated, the combined frequency response of several filters tends to mimic the response of the filter with the lowest cutoff frequency. If you were using an ADC without a digital filter in your application, you might be able to approximate the system noise bandwidth as just the anti-aliasing filter's bandwidth due to its low cutoff frequency. However, since the ADC is downstream from the anti-aliasing filter, you would at least have to calculate a separate noise bandwidth for the ADC.

Let's see how this analysis changes when using an ADC with a digital filter

Digital filter effective noise bandwidth

ADS1261's SINC Filter	
Data Rate (SPS)	60
SINC Filter Order	4
-3dB Cutoff Frequency (Hz)	13
ENBW (Hz)	?





Texas Instruments

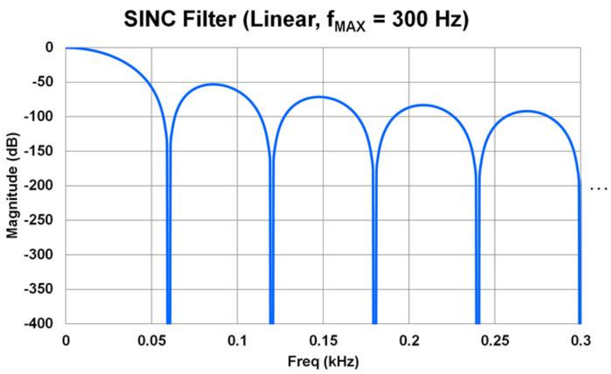
To analyze the combined affect of the anti-aliasing and digital filter, let's use the sinc filter inside the ADS1261, a low-noise, 24-bit delta-sigma ADC. Though this is a commonly-used filter type in many delta-sigma ADCs, this methodology is generally applicable to any ADC with a digital filter.

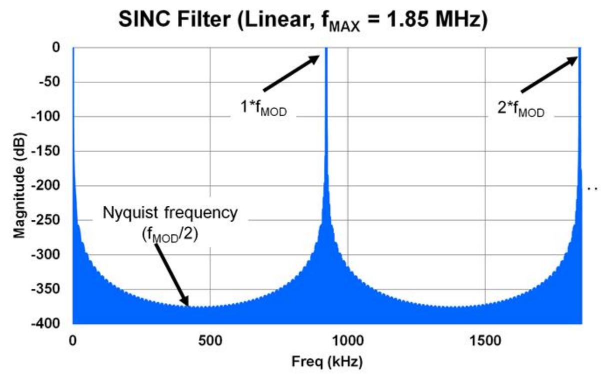
To determine the ADS1261's digital filter noise bandwidth, you first need to set the output data rate and the filter order. Specific values are chosen for this example to clearly illustrate the effect the filter has on the overall noise bandwidth, but the process is the same for any filter type or data rate. This example uses an output data rate of 60 samples per second using the fourth-order sinc filter, which has a 3 dB cutoff frequency of 13 Hz. Importantly, a table of cutoff frequencies by data rate can be found in most ADC datasheets including the ADS1261, requiring no calculation by the user. However, this is not true for the sinc filter's effective noise bandwidth, which must be calculated.

If you look at the sinc filter's frequency response in the ADS1261's datasheet, you would typically see something similar to the plot shown on the right. The sinc filter has notches at regular intervals that are integer multiples of the output data rate. Note that this plot has a linear frequency axis, unlike the anti-aliasing filter plot shown on the previous slide that had a logarithmic frequency axis. This difference complicates the process of combining the filter responses as it prohibits you from simply adding them together point by point. Moreover, a sinc filter response repeats indefinitely. It doesn't simply "stop" at 300 Hz as it might appear on this plot.

If you plotted this sinc filter frequency response over a wider frequency range, you would see some interesting behavior.

Changing f_{MAX} on sinc filter plots





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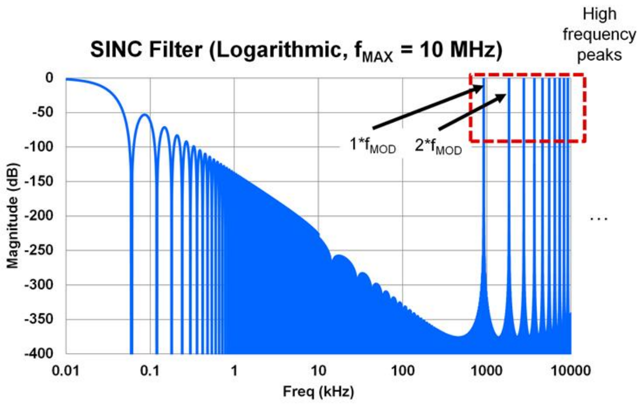
Shown here on the left is the same sinc filter frequency response seen on the previous slide that was taken from the ADS1261's datasheet. This plot is useful to show how the integrated filter rejects multiples of the output data rate, which in this case is 60 samples per second. So, if you want to limit 60 Hz line-cycle noise for example, this filter provides excellent rejection at 60 Hz, 120 Hz, 180 Hz, and so on.

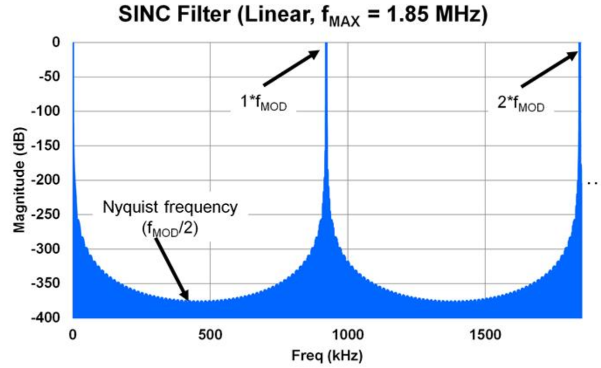
However, if you continue this plot out to a higher frequency range similar to the anti-aliasing filter, the result would be the frequency response shown on the right. Both plots shown here still have a linear frequency axis, though the x-axis in the plot on the left ends at 300 Hz, while the x-axis in the plot on the right extends out to 1.85 MHz. In the plot on the right, you can see more clearly how the sinc filter acts as a lowpass filter out to the Nyquist frequency, at which point the digital filter response begins aliasing until it reaches the modulator frequency, f_{MOD}. Note that f_{MOD} is specific to the ADC, and in the case of the ADS1261 is given by f_{CLK} divided by 8. Using the ADS1261's internal oscillator with a nominal frequency of 7.3728 MHz, f_{MOD} is equal to 921.6 kHz as shown.

As you continue past the first multiple of f_{MOD} in the plot on the right, you can see how the frequency spectrum repeats until the second multiple of f_{MOD}, and would repeat indefinitely given an infinite frequency axis. This is true for either plot shown here, since both represent the same information, just on a different scale.

These repeating high-frequency peaks are important as they complicate the process of defining a sinc filter noise bandwidth. Moreover, in order to combine the sinc filter with the anti-aliasing filter, you must first plot the sinc filter's frequency response on a logarithmic axis

Linear vs logarithmic frequency axis





Integration Limits	f_{ENBW} (Hz)
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10*f_{MOD}	282

$$f_{MOD,ADS1261} = \frac{f_{\mathrm{CLK}}}{8}$$

$$f_{MOD,ADS1261} = \frac{7.3728\ MHz}{8} = 921.6\ kHz$$

Texas Instruments

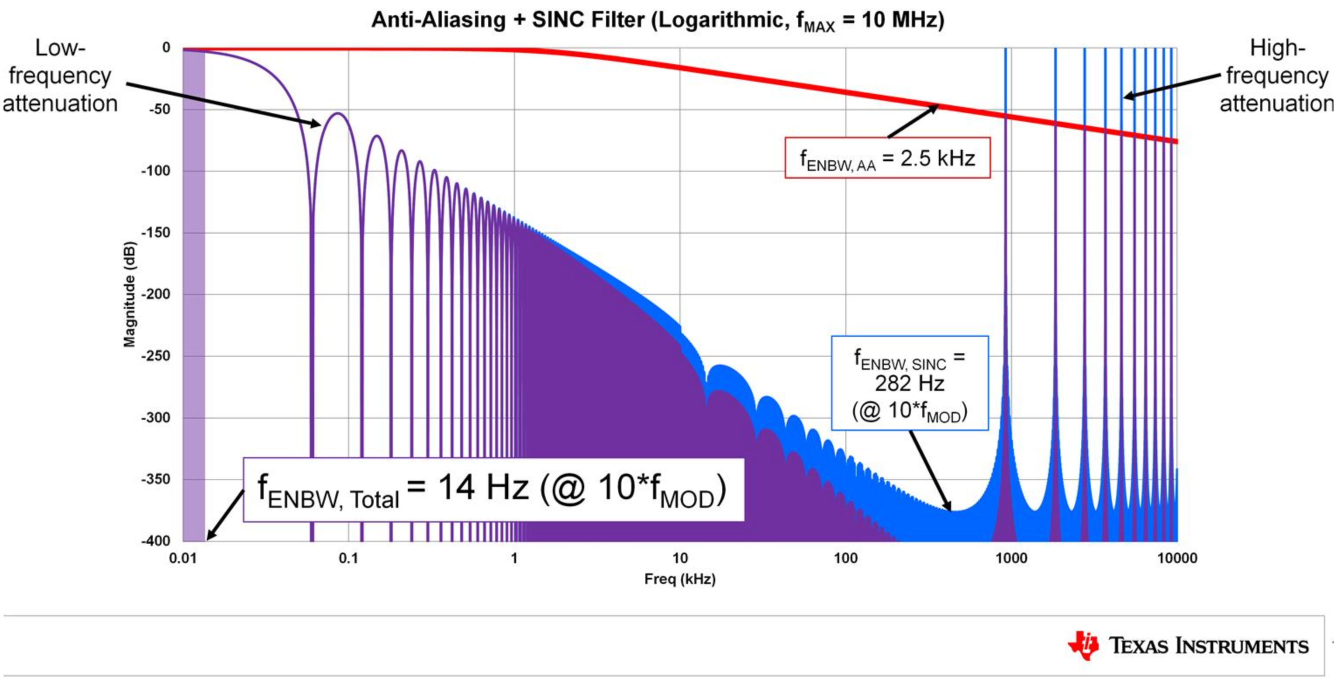
This slide shows the sinc filter plotted in two ways: first, on a logarithmic frequency axis extending out to 10 MHz on the left, and second, on a linear frequency axis extending out to 1.85 MHz on the right. The plot on the right is the same one shown on the previous slide. While the two sinc filter plots shown here look very different, remember that they still represent the same information, just on a different scale.

Importantly, the logarithmic scale allows you to see how the high-frequency peaks at multiples of f_{MOD} continue to repeat. Moreover, you can seen how each new peak allows more noise power to pass through as frequency increases. As a result, if you tried to find the area under this curve using integration, you'd find that the sinc filter's effective noise bandwidth is infinite as shown in the table. From a mathematical perspective, this is due to the fact the integral of the sinc function from zero to infinity does not converge.

How do you continue this analysis given the sinc filter's infinite noise bandwidth? To move forward, you just need to set limits on the integration. With no other filtering in the system, you could determine the sinc filter's practical bandwidth by setting your integration limits to be one or two modulator clock frequencies. As the table on the screen shows, this results in 42 and 70 Hz of noise bandwidth, respectively. Even if you set your limit to 10 multiples of f_{MOD}, which corresponds to the total number of peaks shown on the logarithmic frequency plot, you would realize an effective noise bandwidth of only 282 Hz.

However, recall that the system in this example has an anti-aliasing filter that will limit the noise power seen by the sinc filter. And, since both plots now use a logarithmic frequency axis and are specified in dB, you can add them together point-by-point to realize the combined response.

Combined filter frequency response



Shown on this plot are the frequency responses and individual noise bandwidths for the anti-aliasing filter, in red; the sinc filter, in blue, and the combined response, in purple. Note that the combined response has an effective noise bandwidth of 14 Hz, which is calculated out to 10 multiples of f_{MOD}. This combined noise bandwidth is more than an order of magnitude smaller than the anti-aliasing filter or the sinc filter noise bandwidths using similar limits.

The reason for this much smaller bandwidth is the anti-aliasing filter's attenuation of the sinc filter's high frequency peaks at multiples of f_{MOD}. The anti-aliasing filter removes much of the noise power from the high-frequency peaks that would otherwise fold back into the passband, which is why you don't need to account for the infinite frequency response of the sinc filter. Many analog designers assume that the anti-aliasing filter's intended purpose is to remove lower-frequency noise, when in fact this plot shows this is the sinc filter's responsibility. As discussed earlier in this presentation, designing an anti-aliasing filter with a low cutoff frequency requires larger component values that increase settling time and exacerbates errors due to noise and leakage currents across the filter resistors. Instead, you should target at least 20 to 40 dB of attenuation at the first peak for best performance, which determines the anti-aliasing filter's cutoff frequency.

Another key takeaway from this plot is that the combined filter's effective noise bandwidth is very close to the sinc filter's 3 dB bandwidth, which was 13 Hz. This suggests there may be an approximation for system noise bandwidth that will help avoid significant calculations or integration, similar to the approximations derived in the previous presentation.

To determine if this is true, let’s expand the example to include additional digital filter and anti-aliasing cutoff frequencies.

Approximations for the combined noise bandwidth

ADS1261		System ENBW (Hz)			
Data Rate (SPS)	$f_{C,Digital}$ (Hz)	AA Filter (f_c = 25 Hz)	AA Filter (f_c = 250 Hz)	AA Filter (f_c = 2,500 Hz)	AA Filter (f_c = 25,000 Hz)
2.5	0.58	0.59	0.59	0.59	0.59
5	1.15	1.19	1.19	1.19	1.19
10	2.28	2.37	2.39	2.39	2.39
16.7	3.80	3.92	3.98	3.99	4.31
20	4.63	4.68	4.78	4.78	4.79
50	11	10.72	11.96	11.97	12.09
60	13	12.40	14.34	14.37	14.40
100	22	17.69	23.82	23.96	24.10
400	90	30.87	88.83	95.77	96.16
1,200	272	36.10	196.79	285.11	288.13
2,400	543	37.62	267.42	556.39	574.60
4,800	1,076	38.42	319.89	1026.41	1137.07
7,200	1,580	38.69	340.86	1392.37	1676.52
14,400	2,930	38.95	363.18	2048.71	3077.72
19,200	3,900	39.03	370.23	2353.61	4076.05

If $f_{C,digital} \leq f_{C,AA}$, then
$f_{ENBW,Total} \approx f_{C,digital}$

If $f_{C,digital} \geq 10 \cdot f_{C,AA}$, then
$f_{ENBW,Total} \approx f_{ENBW,AA}$

Otherwise, **no approximation exists**
→ use integration OR
smallest: $f_{C,\ Digital}$ or $f_{ENBW,AA}$

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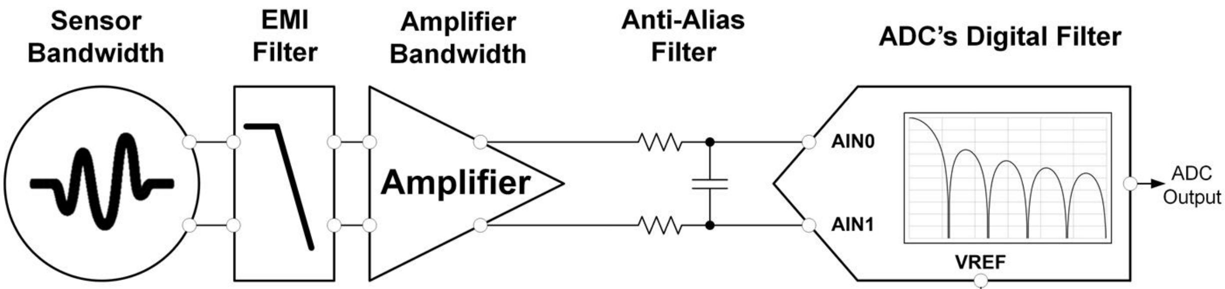
This table shows the ADS1261's cutoff frequencies for all available data rates using the SINC 4 filter, as reported in the ADC's datasheet. Each yellow column represents a different first order anti-aliasing cutoff frequency, from 25 Hz all the way up to 25 kHz. The values in the table are the combined system noise bandwidth for each sinc and anti-aliasing filter cutoff pair. These values can be generally grouped in one of three ways.

The first group, highlighted in blue text, shows where the digital filter's cutoff frequency is less than or approximately equal to the anti-aliasing filter's cutoff. For this group, you can approximate the system noise bandwidth as just the digital filter's cutoff frequency. Comparatively, the values highlighted in red text denote where the digital filter's cutoff frequency is one or more decades *higher* than the anti-aliasing filter's cutoff. For this group, you can approximate the system noise bandwidth as just the anti-aliasing filter's noise bandwidth. In this example, the noise bandwidth of a first order RC filter would be 1.57 times the cutoff frequency. The third group, highlighted in gray text, is such that the system noise bandwidth isn't similar to either the anti-aliasing filter or digital filter cutoff frequency. In this case, no good approximation exists and you must determine the combined system bandwidth using integration or other numerical methods. You could also approximate the system bandwidth as just the digital filter's cutoff frequency or anti-aliasing filter's noise bandwidth, whichever is smaller. This method overestimates the total noise and provides a worst-case value. These approximations are generalized on the right side of this slide.

It should be noted that while the digital and anti-aliasing filter cutoff frequency pairs in this table were chosen to help verify the approximations, they are not necessarily useful in a real circuit. In reality, designers generally choose the anti-aliasing filter cutoff to be higher than the digital filter cutoff due to the analog filter's settling time. You do not want the ADC to sample an unsettled signal, so choosing a higher-frequency cutoff helps ensure the analog filter settles before the ADC is ready to take the next sample. Moreover, as noted on the previous slide, the anti-aliasing filter's purpose is to remove higher-frequency noise, so it is not necessary to use an anti-aliasing filter with a low cutoff frequency in most cases.

As a result, you can further generalize the combined system's frequency response as just the digital filter's 3 dB point, which will be valid for most practical, lower-speed systems. This simplification makes noise analysis easier because the digital filter's 3 dB point is included in the ADC's datasheet, and therefore does not need to be calculated. Furthermore, since the ADC is furthest downstream in the signal chain, the entire *system's* noise bandwidth, from sensor to ADC output, can be reduced to just the digital filter's 3 dB cutoff frequency.

System noise bandwidth



$$V_{N,Total} = \sqrt{\left(V_{NSD,Sensor} * \sqrt{BW_{Sensor}}\right)^2 + \left(V_{NSD,EMI} * \sqrt{BW_{EMI}}\right)^2 + \left(V_{NSD,AMP} * \sqrt{BW_{AMP}}\right)^2 + \left(V_{NSD,AA} * \sqrt{BW_{AA}}\right)^2 + \left(V_{NSD,ADC} * \sqrt{BW_{ADC}}\right)^2}$$

$$if\ BW_{Sensor}, BW_{EMI}, BW_{AMP}, BW_{AA} \geq 10 * BW_{ADC}, then:$$

System noise bandwidth

$$V_{N,Total\ (SNBW)} = \sqrt{\left[\left(V_{NSD,Sensor}\right)^2 + \left(V_{NSD,EMI}\right)^2 + \left(V_{NSD,AMP}\right)^2 + \left(V_{NSD,AA}\right)^2 + \left(V_{NSD,ADC}\right)^2\right] * \mathbf{BW_{ADC}}}$$

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For example, the system presented at the beginning of this module and redrawn here could employ this approximation. The equation for V,N,TOTAL requires the bandwidth seen by each noise source to calculate the system noise. For generic multi-stage filtering systems, you could approximate each bandwidth as the lowest cutoff frequency seen by each component. However, the approximation derived on the previous slide allows you to replace all component bandwidths with the system noise bandwidth, assuming that the digital filter bandwidth is an order of magnitude smaller than all other component bandwidths.

If this condition is satisfied, the system noise bandwidth is just the digital filter's cutoff frequency. This allows you to use the simpler noise equation shown at the bottom of the screen that depends only on the noise spectral densities of each component and the digital filter's 3 dB point. Again, this makes the analysis significantly easier since both the digital filter's 3 dB point and component noise spectral densities are given in the datasheet. Or, as in the case of resistor noise for the filters, are well-known values.

It should be noted that the voltage reference path is not shown here since it is not band-limited by the ADC's digital filter. The voltage reference path therefore cannot employ this additional approximation, so you would need to calculate the bandwidth seen and noise contributed by each component using the principles from the previous presentation.

For either input path, you are now able to analyze, approximate and calculate the resulting noise bandwidth. This allows you to apply the effective noise bandwidth to these components’ noise parameters or noise density plots to give you their overall noise contribution for your system. However, a piece of this analysis is still missing: how do you calculate the noise for both amplifiers as well as the voltage reference? You can check out the Precision Labs modules on these topics to learn more.

Thanks for your time! Please try the quiz.

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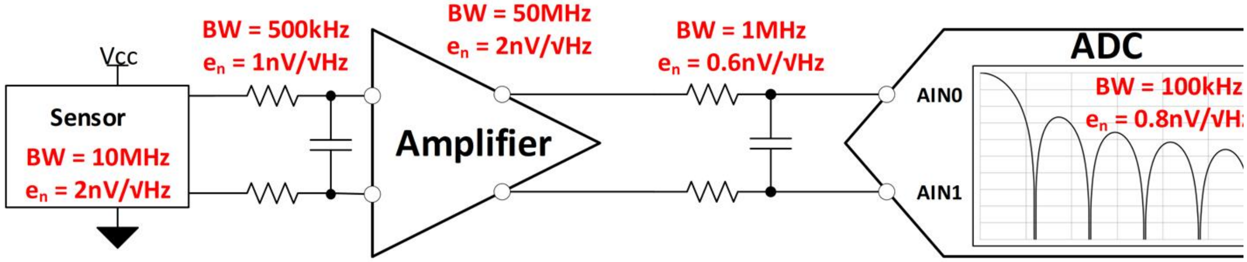
That concludes this video. Thank you for watching. Please try the quiz to check your understanding of this video's content.

Quiz: Noise bandwidth including digital filters

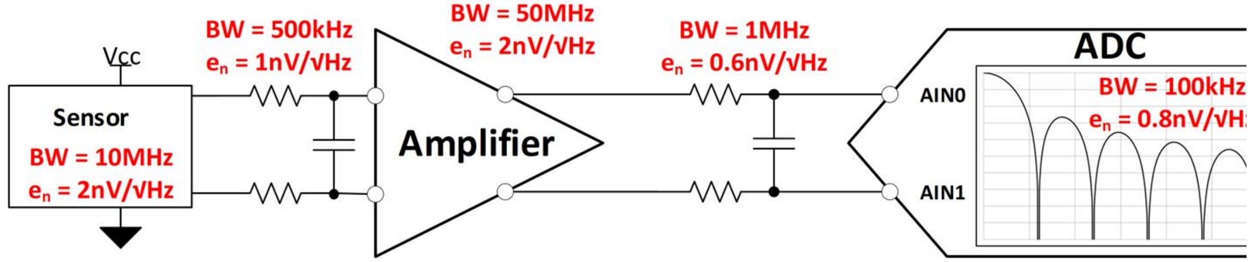
1. What is the cutoff frequency for the system below? What is the noise bandwidth?
   a) 100kHz, 100kHz
   b) 100kHz, 157kHz
   c) 1MHz, 1.57MHz
   d) 10MHz, 15.7MHz
   e) 50MHz, 78.5MHz



Since the digital filter has the lowest bandwidth, is last in the signal chain, and has additional filtering prior to the sinc stage, both the system cutoff frequency and noise bandwidth can be approximated as the cutoff frequency of the digital filter.

Quiz: Noise bandwidth including digital filters

2. Use the circuit from the previous problem. What is the total noise for the system below?
   a) 570nV rms
   b) 1μV rms
   c) 1.25μV rms
   d) 3.45μV rms
   e) 4.85μV rms



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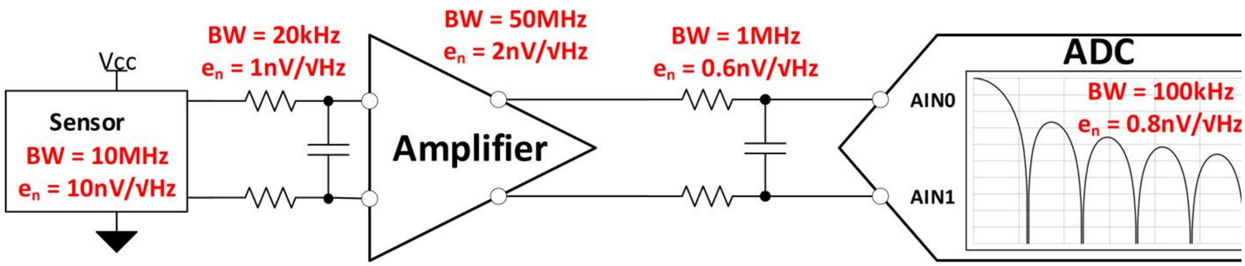
Since you determined that the digital filter has the lowest bandwidth in the previous problem and is last in the signal chain, you can use the digital filter cutoff frequency as the noise bandwidth for all of the preceding devices. To find the total noise, apply this 100 kHz bandwidth to each component in the signal chain and combine the resulting noise values using the root sum of squares method

Quiz: Noise bandwidth including digital filters

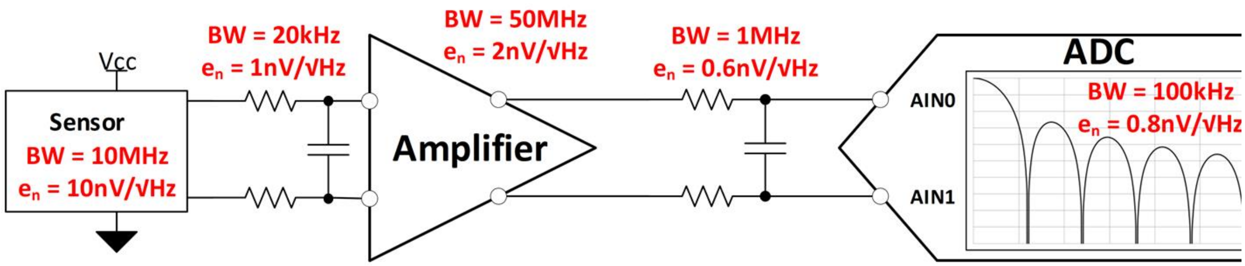
3. What is the effective -3dB bandwidth seen by the sensor below?
   a) 10MHz
   b) 20kHz
   c) 50MHz
   d) 1MHz
   e) 100kHz



The effective bandwidth seen by any component in the signal chain is generally the lowest bandwidth filter that follows this component, which in this case is the RC filter before the amplifier

Quiz: Noise bandwidth including digital filters

4. What is the effective -3dB bandwidth seen by the amplifier in this circuit?
   a) 50MHz
   b) 1MHz
   c) 100kHz



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The effective bandwidth seen by any component in the signal chain is generally the lowest bandwidth filter that follows this component, which in this case is the ADC's digital filter

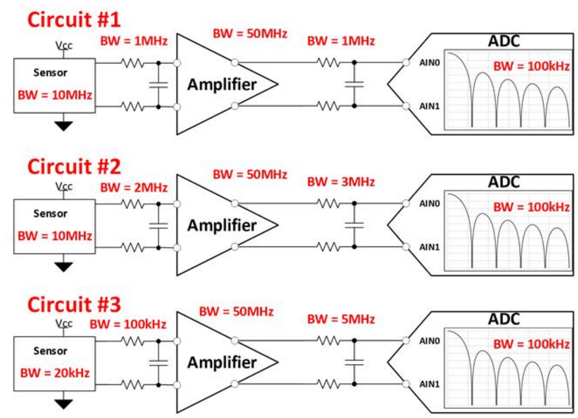
Quiz: Noise bandwidth including digital filters

5. Equation #1 is an approximation that can be used to calculate total noise for many different ADC systems. Which of the three systems below cannot be analyzed using this approximation?

a) Circuit #1
b) Circuit #2
c) Circuit #3
d) The approximation will work for all circuits

Equation #1

$$E_n = (\sqrt{(e_{nSensor})^2 + (e_{nRF\_filt})^2 + (e_{nAmp})^2 + (e_{nADCFilter})^2 + (e_{nDigFilt})^2})(\sqrt{BW_n})$$



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Equation 1 assumes an approximation that the last filter in the signal chain also has the lowest bandwidth. Circuit #3 cannot be analyzed using this approximation since the sensor has the lowest bandwidth in the signal chain, but comes first in the signal chain

Thanks for your time!