AN-2188 Between the Amplifier and the ADC: Managing Filter Loss in Communications Systems

ABSTRACT
This application report discusses managing filter loss in communications systems.

Contents
1 Introduction ................................................................................................................. 2
2 Component Selection for Lowest Losses ........................................................................ 2
  2.1 Inductors .................................................................................................................. 3
  2.2 Capacitors ................................................................................................................ 3
3 Filters ................................................................................................................................ 4
  3.1 Impedance Transformation ....................................................................................... 4
  3.2 Filter Termination ..................................................................................................... 5
  3.3 Creative Filter Selection ................................................................................................ 6
4 ADC Selection .................................................................................................................. 7
5 References ....................................................................................................................... 7

List of Figures
1 Filter-Related Losses ........................................................................................................... 2
2 Using Impedance Transform to Realize Voltage Gain ......................................................... 4
3 Frequency Response for Impedance Transform Filter ..................................................... 5
4 Butterworth Filter with 100Ω Input and 200Ω Output Impedances .......................................... 5
5 Butterworth Filter with Different Input Termination Resistance Values — Filter is Designed for 400Ω Input ......................................................................................................................... 6
6 “Tapped L” Filter ............................................................................................................. 6
7 Various Input Termination Conditions for the Tapped L Filter — Filter was Designed for 100Ω Termination ......................................................................................................................... 7
1 Introduction

Filtering plays an essential part in nearly all communications systems. Removing unwanted signals is part of system design to eliminate unwanted noise or distortion. The signal presented to the analog to digital converter should have no spurs or distortion products, especially outside the desired Nyquist band. Noise and distortion spurs that may be safely outside the band of interest may not remain outside of that band after the ADC sampling process folds them around the sampling frequency.

The primary targets for the final analog filter are broadband noise and harmonic distortion spurs. Broadband noise, in particular, can be problematic since the bandwidth of many ADCs is typically several times the bandwidth of the signals to be processed. Likewise, harmonic spurs from the upper end of the band of interest are typically still within the input bandwidth of the ADC, even though they are far removed from the signal band. If not filtered out these spurs and noise can fold back onto weaker desired signals and mask them.

Designing a filter to pass the desired frequencies is fairly easy. However, one of the largest drawbacks to real filter implementations is the loss of signal through the filter, or insertion loss. This signal loss contributes dB for dB to the ADC noise figure. What may be even worse is that the amplifier driving the ADC will generate distortion at multiples of the filter loss. For example, if a filter has 7dB of loss the amplifier needs to drive a signal 7dB stronger. This will result in second order products with 14dB higher levels and 3rd order products will be 21dB worse. Some of these distortion products (intermodulation in particular) cannot be filtered out, so keeping filter loss to a minimum is critical to system performance.

2 Component Selection for Lowest Losses

One of the first steps of filter optimization is the selection of the center frequency and the bandwidth of the filter. Once this step has been completed the task becomes one of putting the filter elements on the printed circuit board (PCB). PCB design is critical to filter performance, but even before we get to this stage we usually select both the component values and the component sizes we would like to use, this way we can allocate PCB space for the various components. As will be described later, it is very important to choose the filter components first, then make the necessary space available on the PCB, rather than trying to squeeze your filter into the space you have left at the end of the design. The components selected will be critical to the performance of your filter.
2.1 Inductors

Most passive filter designs rely heavily on LC circuit elements. Of all the elements in a filter the inductors probably deserve the most attention. Inductors are usually larger and more expensive than the capacitors and resistors used in a given filter. Often inductors are available only in 10% or 5% values as well. By choosing the inductor first the capacitor values can be chosen to help make up for the more limited selection of inductor values. One thing that becomes clear when one is shopping for inductors, though, is that the physical construction of the inductor presents performance compromises that are more severe than found with the capacitors and resistors that will be used for the filter. For a given value of inductance the inductors available are usually in a package size larger than you would prefer. Taking into account frequency limitations and parasitic effects, though, the smaller sizes offered are often unsuitable for the frequency of operation, and using the wrong components can significantly increase the voltage losses inside the filter.

When selecting an inductor you really need to focus on a few key parameters. The first, of course, is the inductance. When looking for inductors of a given value, keep in mind, that of all passive components inductors have the most constraints with respect to the physical size of the device. While a 100pF capacitor can be found in nearly every footprint, for example, inductors are far more limited. For example, in the CoilCraft catalog for an inductor sized 0.080” x 0.050” one series of inductors is available from 2.5 to 51 nH while another series is available from 0.11 to 22 µH (reference [1]). While this may seem to be a very large range of values, what may not be clear is that the inductor could be specified at a frequency completely different than the frequency at which you intend to use the inductor. For example: The CS series of inductors from CoilCraft use frequencies of 250 MHz to 25 MHz to specify the L values, while the LS series are specified at frequencies of 2.5 MHz to 7.9 MHz.

Finding a component with the correct value of inductance is less than half the battle. One key parameter that is often misunderstood is the Self resonant frequency (SRF). This represents, ideally, the highest frequency at which the inductor is really an inductor. At the self resonant frequency, the inductor has equal amounts of inductive and capacitive reactance. Depending on your application you may be able to use the inductor up to this frequency or slightly beyond. At the very least make sure to model the filter with realistic parasitic values to see if the parasitic capacitance causes the filter to loose performance above the SRF.

When looking at inductor specifications at the signal frequency, don’t forget to research the component performance in the stop band. Having good pass-band performance is important, but having good stop band performance is important as well. The stop band can easily extend well beyond the passband frequency.

In filter design many portions of the circuit are composed of dipoles. The dipole is a circuit element where a capacitor and inductor form a resonant pair that contribute to the frequency response of the circuit. At and near the resonant frequency of these dipole elements there are large currents flowing in the circuit. In order to keep resistive losses low the circuit element must have a good quality factor or “Q”. The Q of an inductor is defined as the ratio of the resistive losses to the inductive reactance. Q must be measured at the frequency of interest because both the inductive reactance and the resistive losses are frequency dependent. Most inductor manufacturers will chart Q vs frequency for their inductors. As a rule of thumb, it is easier to get a high Q inductor when using a physically larger component. This is primarily due to the ability to use a thicker conductor for the inductor to achieve lower resistance.

Many times, for a given inductor size there will be several construction methods to choose from. Wire wound inductors can have an air core or ferrite core. The conductor can be wire wound, thin film or lithographic. Some inductors offer shielding. Other options may include low temperature co-fired ceramic (LTCC) or other more exotic construction methods. Generally speaking, if the inductor has a satisfactory L, Q and SRF the construction method is not a concern.

2.2 Capacitors

We looked at inductors first since they are usually the hardest component to select. The capacitors are, of course, equally critical to the filter design; however, they are usually much easier to select. The key parameters of a capacitor are very similar to those of the inductors. Capacitors also have quality factor and self resonant frequency metrics and they should be selected to equal or exceed the values you used to choose the inductor.
One recent trend in capacitors is to shift the side plates to the long side of the capacitor to gain a much higher Q for a similarly sized capacitor of the more conventional construction. AVX corporation, for instance offers 0204 and 0508 sized capacitors which cut parasitic inductance and resistance (reference [2]).

When selecting filter capacitors it's also a good time to revisit your supply bypass capacitors for the amplifier and ADC. New low loss, high SRF technology will be equally valuable on decoupling capacitors. In order to make the best use of the new capacitor technology it will be very important to ensure that the decoupling capacitors are close to the amplifier or ADC pins. Vias should be avoided if possible due to the inductance they add. Power supply decoupling is really just a fancy name for a low pass filter you place on the device power pins, and before the PCB design is complete is a good time to make other design changes.

Selecting good components with appropriate values and good performance will help keep the power lost in the components to a minimum. If your filter is nearly ideal due to high Q inductors and capacitors and you still find your system performance coming up short there may be some other alternatives for your system to cut the filter related losses. These techniques are described in the following sections.

3 Filters

3.1 Impedance Transformation

When you design an LC filter you normally chose a characteristic impedance for the filter. High-impedance filters tend to be susceptible to noise and parasitic PCB capacitance. High-impedance filters also may have undesirably low values for the capacitors. Designing a low impedance filter usually gives better capacitor values and gives a filter that is less influenced by PCB capacitance. Filters with very low characteristic impedance, however, may be difficult or impossible to drive, due to the currents required. Most communications systems have settled on the range of 50Ω to 400Ω as reasonable impedances for IF filters. For example, the ADC16DV160 has been tested with filters that range from 100Ω to 400Ω with good results.

One common trick with filters is to use the input and output impedances to provide some voltage boost. When there is an ADC on the termination end of a filter you can use voltage gain to offset power loss. The reason this works is that the ADC doesn’t measure power. An ADC (to a first order) can’t tell the difference between 2 Vpp across 100Ωs and 2Vpp across 200Ω. Thus a 100Ω in, 200Ω out, filter could give you enough voltage boost to almost offset 3dB of the 6dB voltage loss of the termination resistors. This technique does have some limitations. Filters with more than a 4:1 impedance transformation ratio are difficult to design and will be sensitive to component tolerances.
3.2 Filter Termination

There is also another option for getting more voltage out of a filter. Filter termination is required for good filter response, however, it is possible to use a filter without matching the impedance of the filter exactly. The degree of filter mismatch will determine the amount of voltage gained and it will also impact the negative effects on the filter response. Figure 5 shows how the trade off works. It is best to match at least one side of the filter with the design impedance. With an amplifier like the LMH6521 or LMH6522 it is very easy to select the filter driving impedance. The LMH6521/22 amplifiers have low output impedance and the filter termination resistors are external so they can be easily changed, which makes system optimization easy.
3.3 **Creative Filter Selection**

Another option for filter flexibility is the topology of the filter. The filter below has an asymmetric response, incorporates impedance transform and is very forgiving of input impedance termination resistance. From the filter response curves it can be seen that this filter will even give a slight voltage gain while keeping a well-behaved response. This filter topology is particularly well-suited for an anti-alias filter since it provides more attenuation on the high-frequency side of the response. It is on this side that the distortion products fall and in many cases the bulk of the amplifier noise falls into the higher frequencies as well.

![Figure 5. Butterworth Filter with Different Input Termination Resistance Values — Filter is Designed for 400Ω Input](image-url)

![Figure 6. “Tapped L” Filter](image-url)
4 ADC Selection

The choice of an ADC can significantly ease the system design. With ever-improving distortion specifications, higher sample rates and noise performance the ADC chosen in a particular application can enable the use of a lower order filter. This filter will have lower loss and will be less susceptible to component variations. Higher ADC sample rates will provide a lot of filter flexibility. For instance, a radio with a 60MHz bandwidth and using a 100 MSPS ADC would gain an additional 25MHz of frequency range by changing to a 150 MSPS ADC. This extra frequency range can be used for filter skirts.

While advancements in high performance, active circuits are making system designs more robust, there is still a need for the use of passive components. Using these filter techniques can make the most of that last passive stage in the signal path.

5 References

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Product | Applications
---|---
Audio | www.ti.com/audio
Amplifiers | www.amplifier.ti.com
Data Converters | www.dataconverter.ti.com
DLP® Products | www.dlp.com
DSP | www dsp.ti.com
Clocks and Timers | www.ti.com/clocks
Interface | www.interface.ti.com
Logic | www.logic.ti.com
Power Mgmt | www.power.ti.com
Microcontrollers | www.microcontroller.ti.com
RFID | www.ti-rfid.com
OMAP Applications Processors | www.ti.com/omap
Wireless Connectivity | www.ti.com/wirelessconnectivity
Appondeal | www.ti.com/appendeal
Automotive and Transportation | www.ti.com/automotive
Communications and Telecom | www.ti.com/communications
Computers and Peripherals | www.ti.com/computers
Consumer Electronics | www.ti.com/consumer-apps
Energy and Lighting | www.ti.com/energy
Industrial | www.ti.com/industrial
Medical | www.ti.com/medical
Security | www.ti.com/security
Space, Avionics and Defense | www.ti.com/space-avionics-defense
Video and Imaging | www.ti.com/video
TI E2E Community | e2e.ti.com

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2013, Texas Instruments Incorporated