

Fast and hot — data converters for tomorrow's software-defined radios

Improvements in mixed-signal and digital technology offer voice and data applications with novel architectures and flexibility.

By Brad Brannon

The last 40 years have seen the active elements of the steadfast superheterodyne radio architecture change from the vacuum tube to transistor to complex integrated circuits. Even now, we are seeing the evolution of semiconductor processes as they move from silicon bipolar and complementary metal-oxide semiconductor (CMOS) to gallium-arsenide (GaAs), and even silicon-germanium (SiGe). Still, the superheterodyne has stayed with us through each generation and as we move to

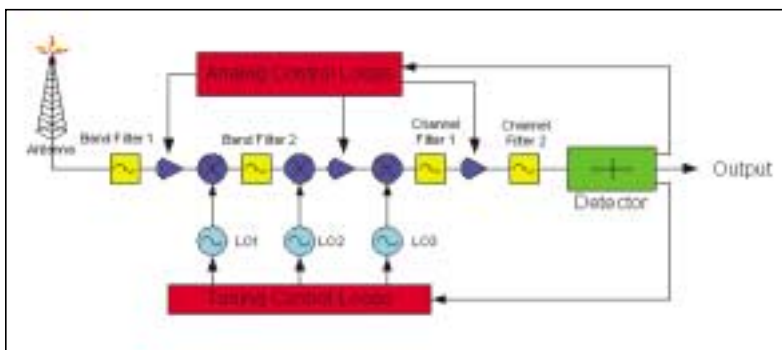


Figure 1. A traditional receiver architecture with analog detection.

newer processes and higher levels of integration, it is poised to prevail in many areas.

The superheterodyne architecture has survived with good reason. It offers consistent performance across a wide band of frequencies because the actual detection occurs at one frequency regardless of the desired carrier frequency. Therefore, the detector itself does not have to operate directly at the RF frequency of interest unlike other architectures.

Adaptation — the superheterodyne's legacy

As transistors and integrated circuit radios came on the scene, the architecture adapted readily to

those technologies and continues to do so today. As air standards became more complicated in an effort to increase information rate and improve reliability, the required detectors became more complicated and eventually were replaced with analog-to-digital converters.

The purpose of the converters is to digitize the complex waveform so that a digital signal processor (DSP) or application-specific integrated circuit (ASIC) can perform the demodulation. Often, two analog-to-digital converters (ADCs) are used to sample the quadrature signals to extract the I and Q signal components for processing.

Many other architectures exist that lend themselves to more flexibility and robustness, including software-defined radios. Often, these include wide-band or IF sampling data converters. These offer many interesting possibilities not feasible with direct traditional implementations. This includes the ability to digitally tune and filter the channel of interest. It is often desirable to optimize the channel filter to the current signal conditions.

Adaptive filtering cannot be done with a fixed ceramic filter found in traditional receiver architectures. Instead, the channel filter can be replaced with a finite impulse response (FIR) filter that can be programmed as needed, thereby constantly optimizing receiver performance.

Baseband sampling applications

In a baseband sampling application, once the signal has been digitized, it can be demodulated in many different ways. Additionally, as the modulation standards change, the DSP program can be updated. This can be seen in the case of half-rate global systems for mobile communications (GSM) or changes in the audio codec. While these are simple examples of software updates, alone they are not examples of software-defined radio. They do, however, begin to hint at what software-defined radio can offer.

Generally, a baseband application will include a channel filter in the form of a SAW filter and a low-pass filter, both of which define the channel characteristics. Thus, while the DSP program can be changed, the RF channel is not free to be changed because the channel filters are part of the analog components. True software-defined radios require that the channel bandwidth be changed.

Dynamic converter performance for these applications is not especially critical because the signals being sampled are low frequency and band limited. Therefore, as long as the converter meets the static requirements to achieve sensitivity, the converter will work fine. Because the main frequency components of this system are at baseband (DC) or very low frequency, the slewing characteristics of these converters are not stressed. However, with the signal component at DC, specifications such as gain and offset are particularly important. For example, if a baseband converter has a large DC offset, this would appear as an unmodulated carrier directly on top of the signal

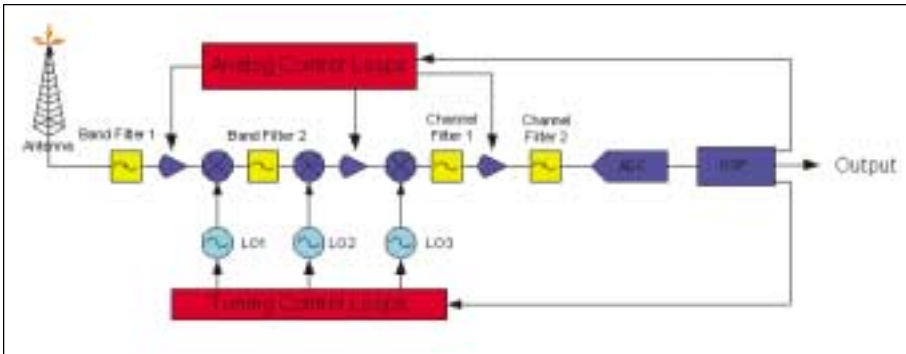


Figure 2. Traditional receiver architecture with digital detection.

of interest. If the signal is large enough, it could completely block the desired carrier.

Likewise, specifications such as integral nonlinearity (INL) and differential nonlinearity (DNL) of data converters can also limit the performance of a receiver. Normally, DNL is considered to contribute to the quantization noise of the ADC. However, at very small signal levels (at or near the reference sensitivity of the receiver), DNL errors can result in apparent gain errors within the ADC, resulting in errors as much as 6 dB. As can be seen in figure 4, the “short” codes result in the ADC generating too many digital codes for the specified input, thus generating the appearance of too much gain.

IF sampling applications

One of the benefits of the super-heterodyne is that all RF signals are converted to a single, low frequency where detection can easily be done. It does, however, require a significant amount of hardware to convert the RF signals down to the detection frequency. In the example above, three down conversions are required. However, if circuitry can be fabricated such that the detection could occur at a higher

frequency, some of the down-conversion stages could be eliminated.

Direct RF detection would be ideal, eliminating all down conversions. While this is a worthy goal, consistent performance would be difficult to achieve. As a compromise, the analog-

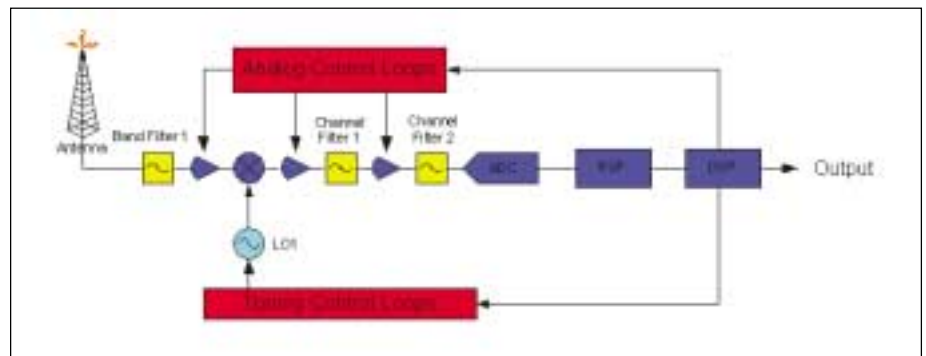


Figure 3. IF sampling receiver with adaptive digital filtering.

to-digital converters may sample the first IF signals.

For IF sampling applications, the first IFs are typically found between 70 and 250 MHz. Typically, 2G, 2.5G and 3G applications all have their IF frequencies in this range. While the baseband ADCs from the previous application can be low-

cost, low-power, low-sample-rate devices, the ADCs used for IF sampling are quite different. They feature fast clocking rates and very wide input bandwidths. While baseband ADCs are often optimized for low-frequency performance with the use of a low pass filter to remove excess noise, IF sampling systems cannot afford this luxury. Here, noise is often reduced by taking advantage of oversampling and digital filtering. By running a very high clock rate relative to the actual signal bandwidth, the noise can be reduced by a process called processing gain. In systems that take advantage of oversampling followed by digital filtering, the apparent SNR of the ADC can be improved by many dB.

Let's talk numbers

For example, if the ADC is sampling a signal at 65 Ms/s and the actual bandwidth is only 200 kHz, the possible ADC SNR improvement is:

$$Process_Gain = 10 \log \left(\frac{65 \times 10^6}{2 \times 200 \times 10^3} \right) = 22.1 \text{ dB} \quad (1)$$

Oversampling with digital filtering gives processing gain. The improvement in SNR is due to the removal of excess noise and signals as shown in Figure 6.

Processing gain is only possible with the use of oversampling and a receive signal processor (RSP)-type function. RSPs are a type of digital integrated circuit that process digital data from an ADC to tune the carrier frequency, perform channel filtering and reduce the data rate. These may be implemented in many different technologies.

The RSP functions like the analog down converter stages it replaces. A closer inspection reveals a digital local oscillator followed by a quadrature demodulator and several filter stages.

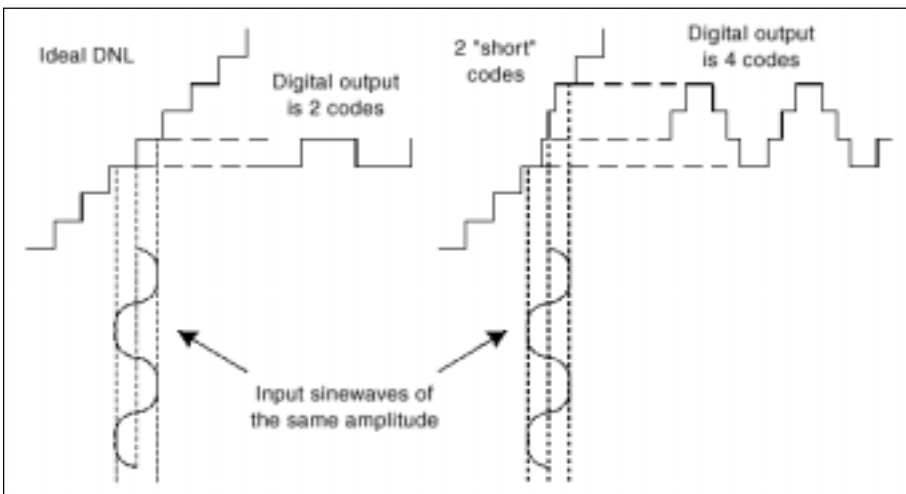


Figure 4. Gain errors that result for DNL errors.

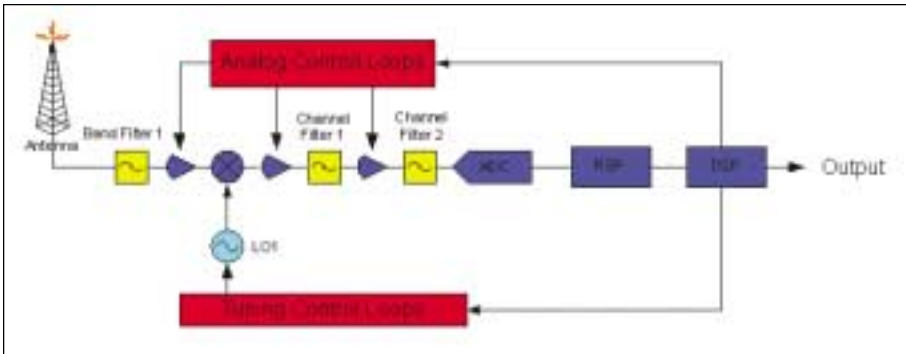


Figure 5. Single-carrier IF sampling.

There are, however, significant functional differences.

The digital advantage

First, this is a digital circuit and is therefore identical from one die to the next. This eliminates alignment and tweaking. Second, because it is digital, it may be programmed. Not only can the local oscillator be tuned, but the filter bandwidths can also be changed, making this device an ideal candidate for software-defined radio.

If the channel filters 1 and 2 shown in the architecture of Figure 5 are

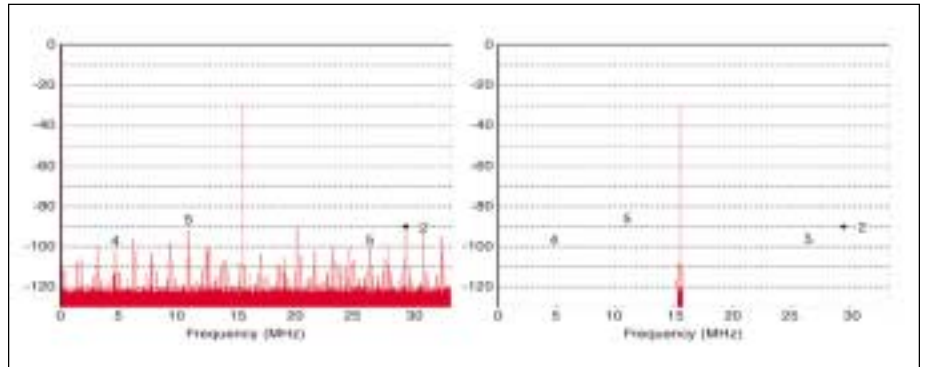


Figure 6. Signal plots both before and after digital filtering.

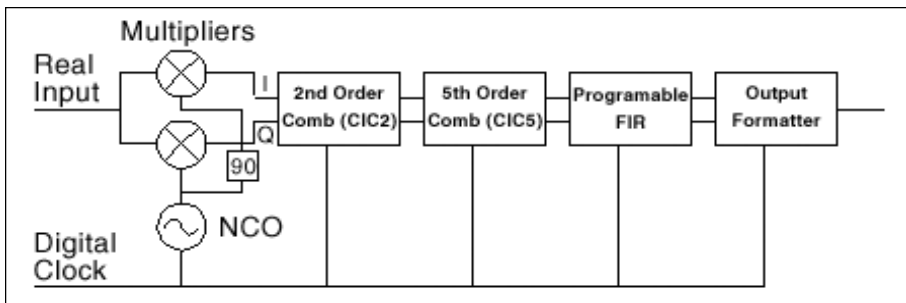


Figure 7. Typical receive signal processor block diagram.

replaced with filters that prevent aliasing within the data converter, then the channel bandwidth is not constrained in the analog domain. It can therefore, be changed in the digital domain. The RSP may then be responsible for channel filtering and rejection of the remaining signals in band. This is a first step toward software-defined radio. In this architecture, the bandwidth, data rate and demodulation method can all be changed, desired characteristics for software defined radios.

In this architecture, the ADC is key to success. While baseband ADCs need not function at high analog input frequencies, this is the norm for this architecture. Therefore these converters must have very wide analog input bandwidth.

In addition to bandwidth, the converters must have good spurious per-

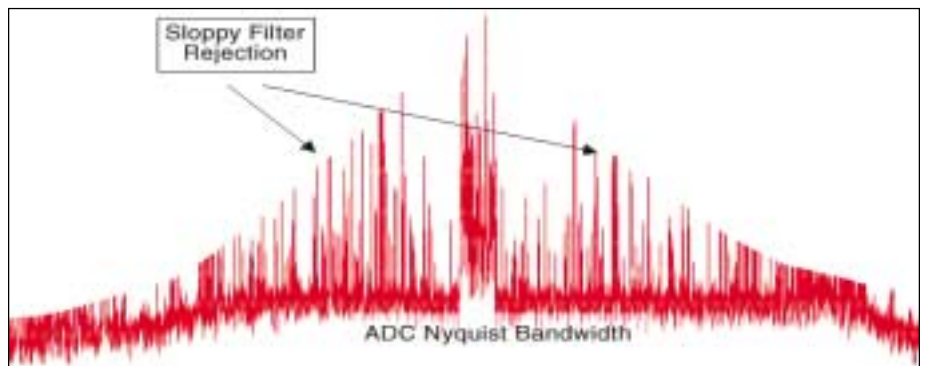


Figure 8. Sloppy IF.

formance. Because there are no analog channel filters, it is possible that a spurious signal generated by an undesired signal may fall into the frequency of interest. If this happens, the channel may be blocked. Therefore, the spuri-

ous performance must be such that any spurs generated are smaller than the desired signals of interest.

In the IF sampling spectrum shown below, very little of the adjacent channel signals are removed with the analog filters. It is the responsibility of the digital filtering from the RSP to remove the un-desired signals. However, undesired signals generated within the ADC

may be difficult to filter.

In the previous example, IF sampling was used to eliminate downconversion stages. There we saw that if the channel filters were relaxed, channel characteristics could be set digitally within the RSP. If the channel filter is further adjusted to provide entire band selection, entire service bands can be digitized. By doing so, it is possible to digitize an entire service band.

Once digitized, the entire band can be digitally tuned and filtered as desired. In

this manner, channel selection, matched filtering, data rate and demodulation standards can all be configured through software, providing a firm beginning for a software-defined radio platform.

Digitizing wide signal bandwidths

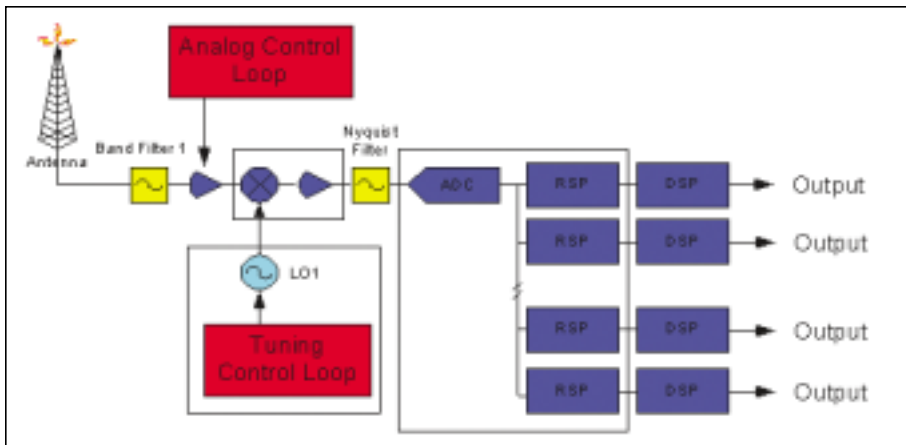


Figure 9. Multicarrier IF sampling.

can be challenging for data converters. In doing so, spurious performance is critical. Unlike single-carrier IF sampling, entire signal bands are digitized, thus allowing potentially hundreds of signals to be digitized. It is important that the converter not generate spurious signals that interfere with the desired signals. These spurious can be in the form of harmonics or intermodulation products. Either way, the results could be poor receiver performance.

One of the first air standards likely to implement a practical multicarrier plat-

form will be wide code-division multiple access (WCDMA). This is possible because of some of the unique spectral properties of CDMA, as well as the relatively controlled spectral environment allocated to these signals. A multicarrier, software-defined approach will allow fine-tuning of the hardware as the standards evolve (and without replacing costly hardware).

Software – when all is said and done

A software-defined radio is one that has the flexibility to tune, filter, set the

About the author

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data rate and control the modulation type through software. The real limitations to these types of systems are the data converters. The back-end digital processing can be implemented in many ways. The analog front end while challenging, it is not impossible.

However, the most critical performer in the system is the data converter. The entire fidelity of the receiver depends solely on this one component. Selected properly, it can solve many problems. Selected improperly, the receiver will not function as desired.

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