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Designing Analog Circuits for Digital Signal Processing

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Digital radios present new design requirements to engineers—this tutorial covers the major issues in digital design, and the requirements of the analog circuitry that delivers the signals to be digitized

In all radio receiver circuits, the primary performance-determining factors are *noise* and *distortion*. All other figures of merit are derived from them. This tutorial article reviews how these factors are handled differently in an all-analog system versus a system where the signal will be digitized for further digital signal processing. Also note that the term "radio receiver" is meant to encompass a wide range of circuits, incuding classic radio communications, test instrumentation, optical and RF cable communications, and various sensor technologies. The receive portion was chosen for this discussion because it involves the widest range of signal levels, along with a wide range of operating conditions that are beyond the control of the designer, such as propagation and interference.

The Analog/Digital Interface and the Digitizing Process

Two recent articles in *High Frequency Electronics* addressed different issues in digital circuits. Dipilato, Terlep and Hofner [1] discussed many pertinent issues with signal preparation for A/D conversion, while Groulx and Mason [2] covered the mechanisms for generation of distortion products in the D/A conversion process. These recent articles are an excellent introduction for the broader look at system design presented here.

Table 1 lists the major factors that digital circuits add to the considerations for design. The first is the noise floor of the system. At first glance, it may seem that the noise floor is an amplitude corresponding to the threshold of the least significant bit. In a simplistic implementation, this may be true, but ADCs benefit from noise dithering, which translates the amplitude of a weak signal into the range of the ADC. The real noise floor is the lowest signal level that can be detected—which is the difference in level required to make a transition from one bit to the next.

Least significant bit (LSB) uncertainty (noise)
Quantization noise due to:
Transition uncertainty (jitter)
Spurious responses
ADC nonlinearities
Total bits available (resolution)
Total accurate bits (dynamic range)
Dithering effects (enhanced weak signal detection)
Clock frequency (Nyquist bandwidth)

Table 1 · Major design factors added by the digitization process.

Dithering can be considered as a cycling of the ADC through different parts of its range, and as a result, extending the overall range. For example, eight bits represents an amplitude range of 48 dB. However, if that ADC can be "biased" by dithering and detect a transition that is one-half of an LSB, another 6 dB is added to its range. This improvement comes at the cost of additional processing power required to handle the additional "bits" equivalent to the increased signal range.

Quantization noise [3] due to errors and nonlinearities in the ADC reduces the system dynamic range, while jitter reduces the "sharpness" of the steps from one logic level to the next. Low jitter allows the greatest improvement with dithering, while poor jitter performance would reduce the enhancement.

The dynamic range of the system is the range from the weakest detectable signal to the strongest. It is very hard to measure dynamic range directly in the digital domain, so it is usually evaluated at the analog input to the ADC, just at it would be for any analog circuit.

The bandwidth of the digitized signal is a maximum of one-half the clock frequency, as determined by Nyquist many years ago. Dithering may reduce the effective bandwidth by "stealing" samples from the ADC. Some designs even use two ADCs to obtain the additional samples.

Real World Signals

Any receiver must deal with the entire range of signals and noise that is present. The theoretical minimum thermal noise at room temperature is –174 dBm in 1 Hz bandwidth. All circuits have a finite noise figure and a bandwidth appropriate to the signals being detected. For a noise figure of 5 dB and a 10 kHz bandwidth, the noise floor in dBm is then:

$$N_{min} = -174 + 10\log(10{,}000) + 5$$

$$= -129 \text{ dBm}$$

At the other end of the range, the strongest signals presented to the receiver will be from nearby spectrum users. This can easily be –10 dBm or higher at multi-user sites, or even between the handsets of users sitting next to one another. With a –10 dBm upper limit, the maximum dynamic range that must be handled becomes:

$$DR = (-10) - (-129)$$

$$= 119 \text{ dB}$$

This corresponds to an ideal 20-bit ADC, which is not practical at this time for high frequencies. This is at the high end of performance capability in analog circuits, as well. The point is that a wide range of amplitudes must be handled if we want reliable communications.

This total dynamic range is reduced somewhat by the amount of distortion on strong signals, created by nonlinearities in the circuit. The reduction of distortion is easily the greatest challenge in achieving the desired dynamic range.

The most common techniques for reduction of distortion and, therefore, maximization of usable dynamic range (often referred to as *spurious-free dynamic range* or SFDR) are:

- Removal of strong unwanted signals by filtering
- The use of high-linearity amplifiers, mixers, switches and other circuit elements
- Applying attenuation or gain to shift signals to the circuit's best-performing range of amplitudes

As we will see in the next section, some of these choices are not well-suited for digitized signals.

System Considerations

A key objective of digitizing signals in modern radios is to reduce the analog circuit content to a minimum. Obviously, this means that there is less opportunity for analog signal processing such as filtering, frequency conversion and gain control. But unless significant strides are made in the dynamic range of ADCs, highly-digital radios must either accept greater analog complexity ahead of the digital circuit, or accept greatly-reduced dynamic range. As of today, both of these scenarios are in play.

Dynamic range is key with digitized radios. A major reason is that digital circuitry does not have the "graceful degradation" of analog circuits. In an analog radio, distortion increases the noise and spurious signal levels, but the desired signal is still present and may even be adequately detected if spurious energy is not located exactly on its frequency.

When all signals fall within the input range of the ADC, digital signal paths react similarly in the presence of distortion, but when strong signals saturate the input to the ADC, all other signals are blocked, since no codes can be output until the strong signal ceases or is reduced.

Since the primary cause of distortion is strong unwanted signals, the above list of methods for reducing distortion all have the objective of eliminating or controlling these signals. Let's look at each in the context of delivering a signal to the ADC:

Filtering

Front-end filtering and IF filtering have been the primary means of achieving the required rejection of unwanted strong signals. However, two objectives of digital radios are wideband frequency coverage and reduction of analog circuitry. The reduction of analog circuitry often means eliminating frequency conversion stages and IF filters. Thus, the ADC is presented with the bandwidth established by the front-end filter.

An analog radio can use a relatively simple front-end filter and a high dynamic range mixer to maintain the necessary signal handling performance prior to the narrowband filtering at the IF. A digital radio may only have the front-end filter ahead of the ADC.

Currently, most high performance digital radios use a downconversion stage ahead of the ADC. One reason is to take advantage of the selectivity afforded by the combination of front-end and IF filtering. The other main reason is to operate the ADC at a lower frequency, where higher-resolution devices are available.

A midway solution is direct conversion (D-C), which can use high dynamic range mixers to convert the RF to baseband (or a low IF), where low-frequency 16-bit ADCs are available with good signal handling properties.

The front-end filter is one of the biggest new challenges for the widest bandwidth digital radio applications, such as software defined radio (SDR) or electronic warfare (EW) systems. These radios rely on wide instantaneous bandwidth, which is essentially unfiltered. However, when focused on a specific task, filtering can be added to enhance operation at that particular frequency and bandwidth. This requires a tunable filter with sufficient flexibility in center frequency and bandwidth—a signficant design challenge.

Another new task for filters that may prove to be the most important is the reduction, or *notching*, of strong unwanted signals. If there are only a few of these strong signals, they may be reduced to levels that allow the ADC to maintain its dynamic range and deliver the full input bandwidth. The notch filters must have sufficient rejection, be frequency agile and accurately tunable. In addition, the system must have the capability of spectrum monitoring to identify the interfering signals and steer the filters.

High Linearity Circuits

As noted above, high dynamic range mixers are a key element in downconversion and direct conversion schemes. Mixer design has advanced to the point where nearly any practical dynamic range can be handled well.

A digital radio with no mixer may require other means of obtaining high dynamic range. One method is to use a preamplifier with a high dynamic range and low noise figure. This boosts signal levels well above the minimum necessary for the ADC. The excess capacity allows for the use of narrow bandwidth front-end filters, which may be quite lossy. It also allows for a flexible range of attenuation, which will be addressed in the next section.

A highly linear preamplifier allows fast, inexpensive solid state switches to be used for both transmit/receive and the selection of analog signal processing options. These switches may only have a loss of a fraction of a dB, but some front-end schemes can cascade several stages of filtering, which increases the loss.

Gain/Attenuation Control

Ultimately, if the ADC does not have sufficient dynamic range, signal levels must be controlled to keep the input within the amplitude range where the ADC has its best performance. While this is a simple concept, its execution in a digital system is not. Analog radios could get by quite well with an IF-derived DC correction signal for automatic gain control (AGC). While not perfect, the time delay between onset of an overrange strong signal and reduced gain was acceptable, being only the propagation delay through the narrowband IF filter, plus the time constant of the DC detection and control circuits.

A digital radio must derive the AGC signal from the data stream, which has a slow response time due to latency through the ADC and following digital signal processor (DSP). Some combination of a fast analog AGC and a more precise digital AGC may be the right solution.

The gain control circuitry can take different forms. A high dynamic range low noise amplifier (LNA) and a digitally-controlled attenuator offers the best performance and precision. These devices are available now. Analog AGC methods using PIN diodes, transistors and ICs are also common and readily available.

Summary and Comments

Digitizing radio signals is an essential part of the advancement of communications technology, as has been demonstrated in numerous wireless applications. As these techniques spread to other applications, and as the analog content of the radios decreases, the design challenges for the remaining analog circuitry change.

The major design differences deal with the restricted dynamic range of current high-speed/high-frequency ADCs. In most cases, that required control must be done within the limitations of much simplified analog circuitry.

Although the goal of some digital radio efforts is to nearly eliminate analog circuitry, practical designs in the near-term will use the well-established analog methods of downconversion and direct conversion to meet performance requirements. It is expected that these techniques will continue for some time when higher performance is needed.

Fully-digital radios with simple analog front-ends will soon become common for applications where a restricted dynamic range and occasional interfering signals can be tolerated. This includes most consumer wireless applications, since the system operator has significant control over signal levels and interference through the number and location of base stations. Eventually, the experience gained from these systems will aid in the next step forward.

References

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