Digital Receivers Bring DSP to Radio Frequencies

With the advent of digital receivers and high speed digitizers, the benefits of modern digital signal processing techniques have become available to radio frequencies. Digital receiver chips perform downconversion, lowpass filtering, and decimation of the sampled RF signal. The resulting bandwidth and sample rate reduction makes it possible to perform real-time calculations, such as FFT spectrum analysis.

Digital receiver chips are available from several manufacturers including Graychip, Intersil and Analog Devices. The first single-chip digital receiver, introduced by Graychip in 1990, was the GC1011 narrowband receiver. Intersil (then Harris) introduced its first chip, the HSP 50016, in 1992. Now there are many digital receiver devices to choose from, as well as IP cores for incorporating this circuitry into gate arrays.

In this article we'll present an overview of the classic analog superheterodyne receiver and compare it with its digital receiver counterpart. If you'd rather not assemble your own boards, you'll be happy to know that off-the-shelf boards and software required to implement digital receiver systems for COTS platforms are now available from board manufacturers. To this end, we'll give you an example of how to assemble the better part of a digital receiver and signal analysis system with boards available from Pentek.

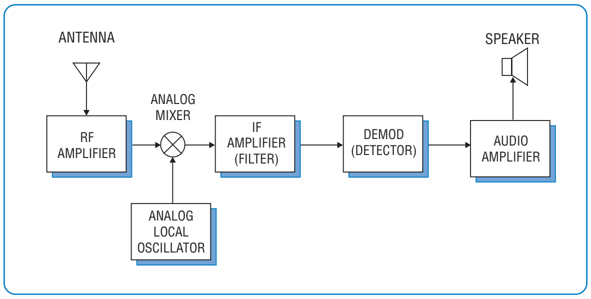

Figure 1. Analog receiver block diagram.

The Analog Receiver

Radio receivers have been around for about one hundred years. While there have been dramatic advances in component technology since the crystal radio, and revolutionary improvements in system architecture such as the superheterodyne circuit, receivers have relied primarily on analog devices for the RF signal path.

During the last 25 years receivers have been equipped with features such as digital readouts for frequency display, and digitally-controlled phase-locked loop synthesizers to replace the older LC local oscillators. Nevertheless, these receivers still employ analog signal processing and do not meet the definition of "digital receiver" as used in this article.

To better understand the differences between analog and digital receivers, let's review the typical block diagram of the traditional analog receiver.

As shown in Figure 1, we need an antenna to pick up the signal from the air. Then we need a tuned radio frequency (RF) amplifier to boost the weak signal from the antenna. Its output is fed into one input of a mixer while the second input comes from an internal variable-frequency local oscillator, known as the LO. When we tune to a station, all we are doing is changing the center frequency of the RF amplifier and the frequency of the LO, to translate the input signal down to a lower frequency, the so-called intermediate, or IF frequency.

This frequency translation is performed by the mixer, which really acts as a signal multiplier. When we multiply two frequencies together, we create both the sum and difference frequencies, as well as some undesirable mixer products. However, by judicious filtering at the mixer output, we can eliminate all but the lowest frequency, which is the difference frequency of the fundamental components of the two input signals.

In order to produce a given IF frequency as the difference frequency, we set the LO frequency equal to the difference between the input channel frequency we wish to receive and the IF frequency. In your home FM receiver, the IF frequency is 10.7 MHz. To tune in a station at 100.7 MHz, the local oscillator could be tuned to 90 MHz or to 111.4 MHz. In both cases, the difference is 10.7 MHz.

Once the input signal has been translated down to the IF frequency, it is sent through the IF stage. This is a tuned, bandpass amplifier aimed at boosting the IF frequency signal, while rejecting the adjacent unwanted stations and all the undesirable byproducts of the mixer. The IF bandwidth of your FM radio is less than 100 kHz, nicely eliminating any adjacent stations which appear at 200 kHz intervals.

The next essential component of a receiver is the detector, or demodulator. In the case of a commercial broadcast station, its function is to extract the information signal, in this case speech or music, from the IF carrier and deliver it to the audio amplifier, which drives the loudspeaker.

This is the basic block diagram of the classic superheterodyne receiver, so named

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because it employs this mixing and downconversion process.

Why all this fancy analog signal processing? Simply because it improves some important parameters of radio reception such as sensitivity, selectivity, S/N ratio, and adjacent channel rejection.

Enter the Digital Receiver

Digital receiver technology has now replaced many of the traditional analog techniques of radio reception. Nevertheless, the same basic principles of signal theory apply as we will see.

Let's take a look at a digital receiver system, such as shown in Figure 2. As you can see, the basic functions of the analog receiver are still there. The signal processing blocks perform high-speed digitization, downconversion, filtering, decimation and demodulation, all done with digital signal processing circuitry. Depending on the type of signal, the demodulator extracts either analog signals or digital data.

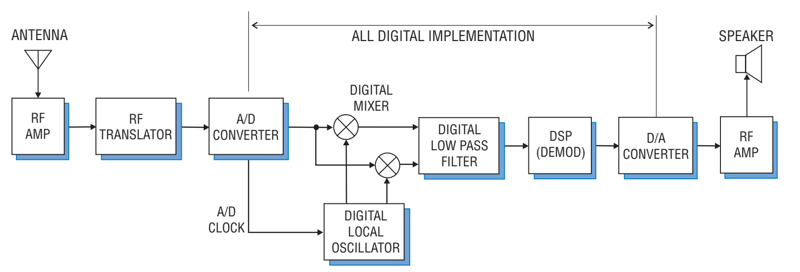

Figure 2. Digital receiver block diagram.

To pluck a weak signal from the air, we still need an antenna and the RF amplifier. If the frequency of the input signal is too high to be digitized by the A/D converter, a RF analog downconversion is also necessary. The resulting input to the A/D converter is either a baseband signal or an IF signal with a bandwidth of typically 45 MHz or less.

Digital samples from the A/D converter at rates up to 100 MHz and higher are now sent into a mixer, just as we did in the analog receiver. Only this time, the mixer is actually two digital multipliers capable of computing output products at the A/D sampling rate. The other inputs to the mixer are digital in-phase (I) and quadrature (Q) components of a local oscillator signal, also arriving at the A/D sampling rate.

The LO is actually a direct digital frequency synthesizer delivering sampled sine and cosine waveforms at a programmable frequency. The LO is driven by the A/D sampling clock and uses a phase accumulator and digital sine lookup table to generate complex output samples.

Just as in the case of the analog receiver, the output of the mixer consists of both sum and difference frequencies and we are interested in keeping the difference product signal. Compared to its analog counterpart, the precision of the digital circuitry in the mixer dramatically reduces unwanted mixer byproducts.

Another distinction in the digital receiver system is that by multiplying the digitized RF input by the sine and cosine signals from the LO, we are performing a single-sideband frequency translation of the input signal. This allows us to translate this complex signal right down to DC or 0 Hz, ideal for the filter which follows.

To select the desired bandwidth of our received signal, we send the mixer output into a complex FIR low pass digital filter. Unlike the IF amplifier filters in the analog receiver, the digital FIR filters are extremely stable, accurate and need no tuning or calibration. They also offer a linear phase response, ideal for time domain signals, and excellent channel-to-channel matching to support applications such as direction finding and beamforming.

By programming the FIR filter coefficients, we can change its bandwidth easily over a wide range. At the filter output, we take advantage of the bandwidth reduction to drop the output sampling rate, a process called decimation.

Since the bandwidth and decimation are linked, many digital receivers allow simple control of both, through a parameter called the decimation factor N. The final output bandwidth of the FIR filter is determined by dividing the A/D sampling rate by N, making it quite easy to program.

Digital receivers can be divided into two classes. Narrowband receivers typically have a decimation range of about 32 to 65,536 and, therefore, provide output bandwidths from below 1 kHz to about 2.5 MHz for sampling at 100 MHz. Wideband receivers, with decimation factors ranging from 1 to 64, can deliver bandwidths from approximately 2 MHz up to about 45 MHz.

Depending on the digital receiver chip used, the output formatter stage can provide either real or complex digital outputs in 16-, 24-, or 32-bit fixed point or IEEE floating-point data formats to match the needs of the DSP stage which follows.

As far as the demodulator function is concerned, it is now performed digitally in a DSP processor. For standard commercial broadcast stations, envelope detection algorithms can handle AM signals and fre-

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quency discriminator algorithms can handle FM signals. The demodulated sampled outputs can be sent into a D/A converter to produce an analog signal and then connected to an amplifier and speaker.

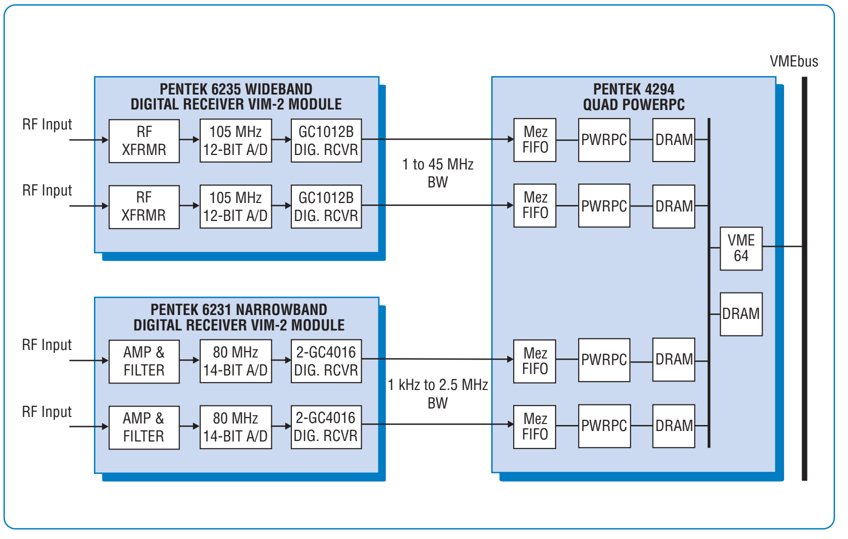

Figure 3. Multichannel receiver and signal analysis system.

Widespread use of radio transmissions of digital data now supports booming markets for cell phones, pagers, wireless LANs, satellite communication and HDTV, to name just a few. Here, the benefits of digital receivers can really shine.

Digital data transmission employs dozens of different schemes for encoding phase, amplitude and frequency, each scheme targeted for a specific application. On the receiving side, demodulation tasks for the DSP processor include channel equalization, symbol tracking, frame detection, convolution, error correction, decoding, and decompression. No approach other than digital signal processing could possibly handle these tasks.

Because they are inherently programmable, as new modulation standards are invented, digital receiver systems can often be upgraded by loading new software routines instead of replacing expensive hardware.

The other major benefit of digital receiver systems is the economy of scale for high channel count systems. While it may still be cheaper to use an analog receiver in your Walkman, a cell phone base station takes full advantage of low cost per channel, low power, improved accuracy and stability, high reliability, reconfigurability and fast switching characteristics offered by digital receiver technology.

A Signal Analysis System

Pentek offers a full range of catalog COTS board-level products for complete digital receiver systems including A/D converters, digital receivers, DSP processors, and peripherals providing various analog and digital interfaces. Let's look at an example of a digital receiver subsystem using some exciting new VIM architecture products for the PowerPC processors.

As shown on Figure 3, we use two different VIM mezzanine modules, mounted on a quad PowerPC floating-point RISC processor board. In the upper left, the wideband digital receiver module includes two identical channels consisting of a RF transformer, a 12-bit 105 MHz A/D converter, and a Graychip CG1012B digital receiver chip. Each channel is connected over the VIM mezzanine connector directly into its own processing node, which is capable of executing up to 4.5 billion floating point operations per second. The VIM mezzanine easily handles the 45 MHz maximum wide-band digital outputs this module delivers.

In the lower left, the narrowband digital receiver module has the same circuitry as the narrowband module but uses two quad Graychip GC4016 narrowband receiver chips for each input. The VIM mezzanine has to handle only 2.5 MHz bandwidth in this case.

In this system, two complete narrowband receivers and two complete wideband receivers along with an 18 GFLOPS processor board occupy only a single VMEbus slot. This channelized approach, with all functions on one board, represents a huge benefit for system density and cost.

As stated before, the advantage of using digital receivers is the downconversion and resulting reduction in bandwidth and sample rate. These make it possible to perform real-time calculations with the processor. As shown in Figure 4, a FFT calculation of the receiver output signal is an actual "zoomed-in" view of the selected slice of the input RF spectrum. The position and bandwidth of the slice are programmed by setting the LO frequency and decimation factor of the digital receiver.

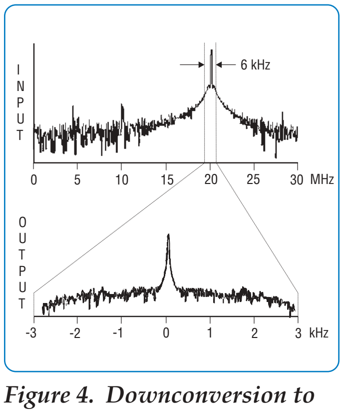

Figure 4. Downconversion to baseband.

Digital Receiver Applications

These new digital receivers offer an excellent solution when digital signal processing is required for signals contained in a certain frequency band of a wideband RF signal. This is typical of many frequency-division multiplexed communication systems, modem modulation schemes and many forms of radar signals. By taking advantage of the receiver hardware to selectively remove out-of-band data, the signal processing demands of more expensive DSP hardware can be dramatically reduced. ❑