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Design Issues for Direct-Conversion Wireless Radios

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Direct-conversion radios are the norm for many new handsets, saving space, cost and power consumption — which is now available to support additional customer-oriented features

Direct-conversion (D-C) is the chosen architecture for many, perhaps most, new designs for cellular/PCS/3G radios, plus many WLAN and other wireless devices. D-C (also called "zero-IF") has reached this level of acceptance because of its ability to reduce the size, parts count and cost of the radio portion of wireless devices.

The path between concept and execution of a D-C radio was not simple. There are several difficulties with the simplified architecture of D-C that limit its ultimate performance. This tutorial article takes a look at the design issues that give D-C its advantages, and those that require special attention to minimize compromises in performance.

The Basics of Direct-Conversion

Figure 1 shows the simplest form of a direct-conversion receiver (or transmitter, if the signal path is reversed). The simplicity is obvious, especially when compared to a typical superheterodyne architecture. The desired signal is applied to the input port of a mixer (acting as a product detector). A local oscillator at the input signal's center frequency f_c creates a mixer output with a frequency of zero at f_c plus and minus any modulation and noise sidebands, and including frequency-translated versions of all other signals and noise that are passed by the input filter.

The output of the mixer/detector is processed to extract only the desired information. Gain, filtering, limiting, rectification, etc. are applied as needed, depending on the nature of the signal's modulation. The simplicity of D-C is striking, but that simplicity comes with some limitations, which will be explored next.

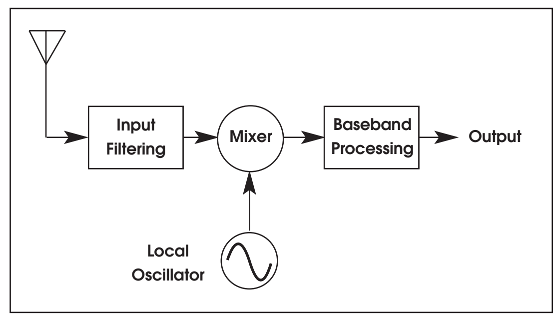

Figure 1 · The simplest D-C circuit "directly-converts" an input frequency to baseband.

The 'Missing' IF Functions

In a typical superhet, the IF circuitry is very important. This is where the channel filtering is implemented, where most of the signal path gain is inserted, and where AGC or limiting is applied.

Channel filtering—The front-end filter only eliminates frequencies well-separated from f_c, so an IF usually includes a narrowband filter to separate individual communications channels. Crystal, ceramic or SAW filters are typically used here, with appropriate bandwidths for the application.

In a D-C radio, this filtering must be accomplished at baseband. If the baseband processing includes DSP, as is the case with virtually all commercial wireless devices, implementing the necessary filter algorithms is a straightforward matter.

Automatic Gain Control (AGC)—While

AGC can easily be accomplished using baseband DSP, there is one highly significant issue: The time constant of the AGC must be faster than most of the frequency components of the signal. With a conventional IF, the AGC feedback loop may take many cycles to extract the control voltage, but at 10.7 MHz or higher, this is but a fraction of one cycle of the signal envelope.

Solutions include complex algorithms to generate AGC from baseband, high dynamic range circuitry that requires little AGC, and the use of logarithmic amplifiers that compress the amplitude range and reduce or eliminate the need for AGC. Constant-carrier modulation formats like BPSK and wideband FM can get by with limiters instead of AGC, but these are mainly used in the simplest types of wireless equipment.

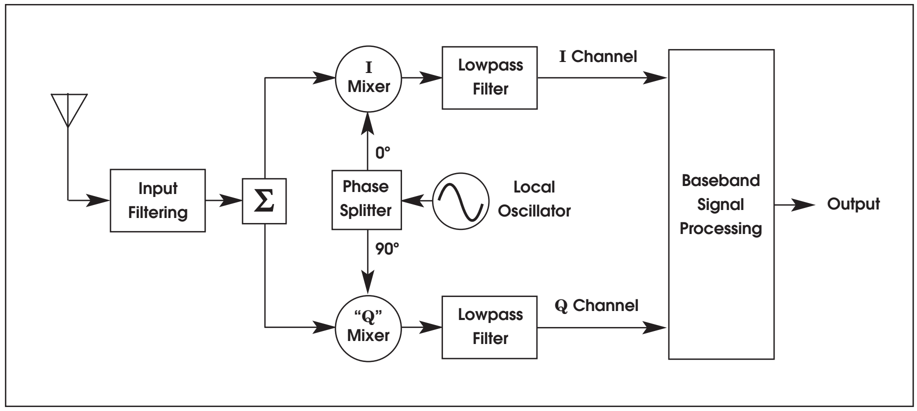

Figure 2 · Two signal paths and quadrature (90°) phase shifts comprise a typical D-C circuit used in current wireless products.

Gain distribution—Without an IF, the only options for providing the necessary gain are at the front end and after the detector, at baseband. High gain at the signal frequency is not practical. It is an invitation to oscillation, and with strong signals it can easily exceed the dynamic range of the mixer/detector input. Some amount of front end gain is required, even with a superhet design, to make up for the losses in switching and duplexer filters.

Providing a lot of gain at baseband is more difficult than at IF. With signal components at frequencies down to DC, a baseband amplifier must have exceptional power supply isolation and the system must have very low noise at low frequencies. High gain will amplify small ripples on signal, power and ground, caused by circuit elements such as DC-DC converters, voltage regulators, and digital clocks. Some capacitors have microphonic responses and need to be avoided.

Image Frequencies

The simple D-C circuit of Figure 1 is like any mixer, having outputs at both the sum and difference of the input and LO frequencies. In a superhet, one of these frequency-converted images is removed by filtering. Virtually all practical D-C radios use in-phase and quadrature (I-Q) techniques to remove the unwanted image by phase- and amplitude balance methods. Figure 2 shows how this is implemented in a receiver. Any modulation format can be created or recovered using the I-Q technique.

The lowpass filters following the mixers are usually simple, low-order types that avoid "bleed-through" of RF and LO, and eliminate the downconverted energy of signals that are outside the channel, but not attenuated sufficiently by the input filter. These post-filters may be part of the DSP in some D-C systems.

I-Q radios rely on precise control of amplitude and phase of each channel to achieve maximum performance. Analog implementations can easily maintain less than 1° phase error and a couple tenths dB of amplitude balance. This is adequate for voice communications quality, but not for the data rates and reliability of 3G wireless. Again, DSP comes to the rescue, not only with precise control of phase and amplitude, but with adaptive monitoring and calibration algorithms that maintain accuracy over the expected ranges of time, temperature and battery voltage.

LO Radiation

With the LO on the operating frequency, the input filter will not prevent the LO from passing through to the input. The balance of the mixers becomes the controlling factor. An isolator in the input circuitry will further reduce LO feedthough.

Advantages of Direct Conversion

OK, once the chip and system designers have determined how to deal with the design issues of D-C radios, are there advantages beyond the simplicity of the circuit?

The answer is "yes," starting with cost. As noted at the beginning, parts count is dramatically reduced in the RF portion of a D-C radio compared to a superhet design. Most of the added complexity to deal with D-C limitations is inside the DSP chip, which only needs to be done once for millions of handsets, and will be fabricated on the low-cost silicon.

Some other notable advantages include the following:

No frequency limits—Within the bandwidth of the mixer/detectors and the LO phase splitter, a D-C radio can operate on any frequency. The front-end filter can even be eliminated if necessary. Swept receivers, such as those in spectrum and network analyzers can be implemented with D-C techniques.

Minimal spurious responses—Spurious responses are the result of unwanted mixing products caused by nonlinearities and imperfect isolation. In a D-C radio, the only significant spurs are at the harmonics of the LO, which are far removed from the operating frequency.

High linearity—Distortion is minimized in a D-C architecture, due both to the short signal path as well as the elimination of the narrow IF filter, which usually increases time-domain distortion.

An Alternate Type of D-C

Although beyond the scope of this article, it should be noted that I-Q is not the only method for signal generation and demodulation in a D-C radio. All modulation formats can also be represented using vector techniques, where the signal is defined in terms of magnitude and angle. Devices using this technique have been developed, but are not yet widespread in their implementation.