IP_2 and IP_3 Design Considerations for a Direct Conversion I/Q Receiver

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This article analyzes the levels of 2nd and 3rd order distortion products and their effects on a direct conversion I/Q receiver in a WCDMA application

Direct conversion receiver architecture offers several advantages over the traditional superheterodyne. It eases the requirements for RF front-end bandpass filtering, as it is not susceptible to signals at the image frequency. The bandpass filters need only attenuate strong out-of-band signals to prevent them from overloading the front end. Also, direct conversion eliminates the need for IF amplifiers and bandpass filters. Instead, the RF input signal is directly converted to baseband, where amplification and filtering are less difficult. The overall complexity and parts count of the receiver are reduced as well.

Direct conversion does, however, come with its own set of implementation issues. For example, since the receive LO signal is at the same frequency as the RF signal, it can easily radiate from the receive antenna and violate regulatory standards.

Unwanted baseband signals can also be generated by 2nd order nonlinearity of the receiver. A tone at any frequency entering the receiver will give rise to a DC offset in the baseband circuits. Once generated, straightforward elimination of DC offset becomes very problematic because the frequency response of the post-downconversion circuits must often extend to DC. The 2nd order nonlinearity of the receiver also allows a modulated signal, even the desired signal, to generate a pseudo-random block of energy centered about DC.

Unlike superheterodyne receivers, direct conversion receivers are susceptible to such 2nd order mechanisms regardless of the frequency of the incoming signal. So minimizing the effect of finite 2nd order linearity is critical to the design of such receivers.

Later in this paper we will consider the effect of 3rd order distortion on a direct conversion receiver. In this case, two signals separated by an appropriate frequency must enter the receiver in order for unwanted products to appear at the baseband frequencies.

Second Order Distortion (IP_2)

The second order intercept point (IP_2) of a direct conversion receiver system is a critical performance parameter. It is a measure of second order non-linearity and helps quantify the receiver's susceptibility to single and two tone interfering signals. Let's examine how this nonlinearity affects sensitivity.

We can model the transfer function of any nonlinear element as a Taylor series:

$$y(t) = x(t) + a_2x^2(t) + a_3x^3(t) + \ldots$$

where $x(t)$ is the input signal consisting of both desired and undesired signals. Consider only the second order distortion term for this analysis. The coefficient a_2 is equal to $\sqrt{[2/(Z_oIP_2)]}$ where IP_2 is the single tone intercept point in watts. The more linear the element, the smaller a_2 will be. Note that the two-tone IP_2 is 6 dB below the single-tone IP_2.

Every signal entering the nonlinear element will generate a signal centered at zero frequency. Even the desired signal will give rise to distortion products at baseband. To illustrate this, let the input signal be represented by:

$$x(t) = A(t)\cos\omega t$$

which may be a tone or a modulated signal. If it is a tone, then $A(t)$ is simply a constant. If it is a modulated signal, then $A(t)$ represents the signal envelope.

By definition, the power of the desired signal is $1/Z_o$ * $E\{(A(t)\cos\omega t)^2\}$, where $E\{\beta\}$ is the expected value of β. Since $A(t)$ and $\cos\omega t$ are statistically independent, we can expand $E\{(A(t)\cos\omega t)^2\}$ as $E\{A^2(t)\}$ * $E\{\cos^2\omega t\}$. By trigonometry this is equal to $E\{A^2(t)\}$ * $E\{1/2 + (1/2)\cos 2\omega t\}$. The expected value of the second term is simply 1/2, so the resulting product is 1/2 * $E\{A^2(t)\}$. The power of the desired signal simplifies to:

$$P_s = 1/(2Z_o) * E\{A^2(t)\} \qquad (1)$$

In the case of a tone, $A(t)$ may be replaced by A. The signal power is, as expected, equal to $A^2/(2Z_o)$.

In the more general case, the desired signal is digitally modulated by a pseudo-random data source. We can represent it as band-limited white noise with a Gaussian probability distribution. The signal envelope $A(t)$ is now a Gaussian random variable. The expected value of the square of the envelope can be expressed in terms of the power of the desired signal as:

$$E\{A^2(t)\} = 2Z_oP_s \qquad (2)$$

Now substitute $x(t)$ into the Taylor series expansion to find $y(t)$, which is the output of the nonlinear element:

$$y(t) = A(t)\cos\omega t + a_2\,(A(t)\cos\omega t)^2 + \ldots\text{higher order terms}$$
$$= A(t)\cos\omega t + (1/2)a_2A^2(t) + (1/2)a_2A^2(t)\cos 2\omega t + \ldots$$

Consider the 2nd order distortion term $(1/2)a_2A^2(t)$. This term appears centered about DC, whereas the other 2nd order term appears near the 2nd harmonic of the desired signal. Only the term near DC is important here, as the high frequency tone will be rejected by the baseband circuitry.

In the case where the signal is a tone, the 2nd order result is a DC offset equal to:

$$\text{DC offset} = (1/2)a_2A^2 = a_2P_sZ_o \qquad (3)$$

If the desired signal is modulated, then the 2nd order result is a modulated baseband signal. The power of this term is $1/Z_o$ * $E\{[(1/2)a_2A^2(t)]^2\}$. This can be expanded to:

$$P_{bb} = a_2^{\,2}/(4Z_o) * E\{A^4(t)\} \qquad (4)$$

In order to express this result in terms of the desired signal power, we must relate $E\{A^4(t)\}$ to $E\{A^2(t)\}$. For a Gaussian random variable, the following relation is true:

$$E\{A^4(t)\} = 3 * [E\{A^2(t)\}]^2 \qquad (5)$$

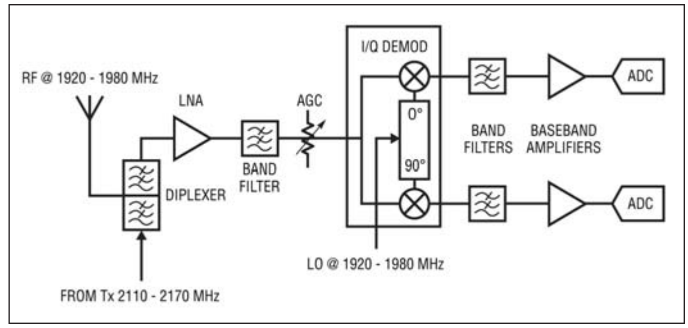

Figure 1 · Block diagram of a typical WCDMA base station receiver.

The distortion power can then be expressed as $3a_2^{\,2}/(4Z_o) * [E\{A^2(t)\}]^2$. Now express the expected value in terms of the desired signal power:

$$P_{bb} = 3a_2^{\,2}Z_oP_s^{\,2} \qquad (6)$$

It is the conversion of any given tone to DC and any modulated signal into a baseband signal that makes second order performance critical to direct conversion receiver performance. Unlike other nonlinear mechanisms, the signal frequency does not determine where the distortion product falls.

Any two signals entering the nonlinear element will give rise to a beat note/term. Let $x(t) = A(t)\cos\omega t + B(t)\cos\omega_u t$, where the first term is the desired signal and the second term is an unwanted signal.

$$y(t) = A(t)\cos\omega t + a_2(A(t)\cos\omega t + B(t)\cos\omega_u t)^2 + \ldots$$
$$= A(t)\cos\omega t + (1/2)a_2A^2(t) + (1/2)a_2A^2(t)\cos 2\omega t + 2a_2A(t)B(t)\cos\omega t\cos\omega_u t + \ldots$$
$$= A(t)\cos\omega t + \ldots + a_2A(t)B(t)\cos(\omega - \omega_u)t + \ldots$$

The second order distortion term of interest is $a_2A(t)B(t)\cos(\omega - \omega_u)t$. This term describes the distortion product centered about the difference frequency between the two input signals. In the case of two unwanted tones entering the element, the result will include a tone at the difference frequency. If the two unwanted signals are modulated, then the resultant includes a modulated signal centered about their difference frequency.

We can apply these principles to a direct conversion receiver. The block diagram of a typical WCDMA base station receiver appears in Figure 1. Here are some key characteristics of this example:

Base Station Type:	FDD, Band I
Base Station Class:	Wide Area
Number of carriers:	1
Receive band:	1920 to 1980 MHz
Transmit band:	2110 to 2170 MHz

The RF section of this receiver includes a diplexer, a bandpass filter, and at least one low noise amplifier (LNA). The frequency selective elements are used to attenuate out-of-band signals and noise. The LNA(s) establishes the noise figure of the receiver. The I/Q demodulator converts the receive signal to baseband. In the examples illustrated later in this paper, we will use the characteristics of the LT5575 I/Q demodulator as representative of a base station class device of this type. Lowpass filters and baseband amplifiers band-limit and increase the signal level before it is passed to the A/D converters. The diplexer and RF bandpass filter serve as band filters only; they do not offer any carrier selectivity.

The second order linearity of the LNA is much less important than that of the demodulator. This is because any LNA distortion due to a single signal will be centered about DC and rejected by the demodulator. If there are two unwanted signals in the receive band (1960 MHz, for example), then a second order product will be generated by the LNA at the difference frequency. This signal will be demodulated and appear as a baseband artifact at the A/D converter. We need not address this condition, however, because out of band signals emerging from the front-end diplexer will not be strong enough to create distortion products of any importance.

Consider first a single unmodulated tone entering the receiver (see Figure 2).

As detailed above, this tone will give rise to a DC offset at the output of the demodulator. If the baseband cascade following the demodulator is DC-coupled, this offset will be applied to the A/D converter and reduce its dynamic range. The WCDMA specification (3GPP TS 25104.740) calls out an out-of-band tone at –15 dBm, located 20 MHz or more from either receive band edge (section 7.5.1). Compute the DC offset generated in the I/Q demodulator:

Tone entering receive antenna port:	–15 dBm
Diplexer rejection @ 20 MHz offset:	0 dB
Bandpass rejection @ 20 MHz offset:	2 dB
RF gain preceding LT5575:	20 dB
Tone entering LT5575:	+3 dBm
LT5575 IIP_2, two tone:	+60 dBm
LT5575 a_2:	0.00317
DC offset at LT5575 output:	0.32 mV
Baseband voltage gain:	31.6
DC offset at A/D input:	10 mV

Single WCDMA carriers can also serve as interferers, as detailed in section 7.5.1. In one case, this carrier is offset by at least 10 MHz from the desired carrier but is still in the receive band. The power level is –40 dBm, and the receiver must meet a sensitivity of –115 dBm for a 12.2 kbps signal at a BER of 0.1%. Here are the details:

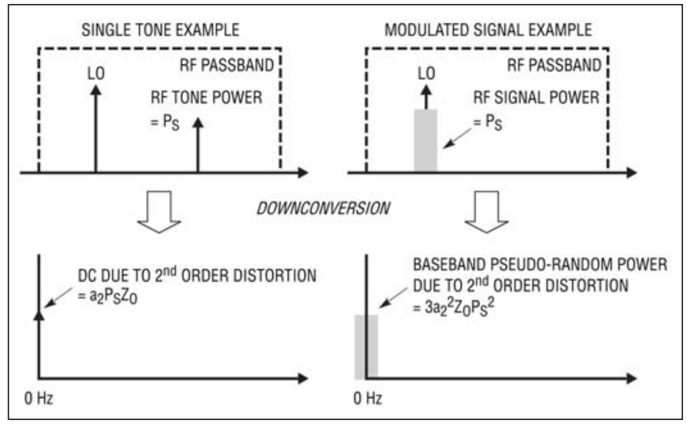

Figure 2 · Effects of 2nd order distortion.

Signal entering receive antenna port:	–40 dBm
RF gain preceding LT5575:	20 dB
Signal entering LT5575:	–20 dB
LT5575 IIP_2, two tone:	+60 dBm
LT5575 a_2:	0.00317

A MATLAB simulation performed using a pseudo-random channel predicts the following:

Distortion at LT5575 output:	–98.7 dBm

This result agrees well with that given by Equation 6, which predicts a distortion power of –98.2 dBm.

The baseband product that appears at the LT5575 output is a noiselike signal, created from the interfering WCDMA carrier. If this signal is large enough, it can add to the thermal receiver and A/D converter noise to degrade sensitivity. Compute the equivalent thermal noise at the receiver input with no added distortion:

Sensitivity:	–121 dBm
Processing + coding gain:	25 dB
Signal to noise ratio at sensitivity:	5.2 dB
Thermal noise at receiver input:	–101.2 dBm

Now refer the distortion signal back to the receiver input:

RF gain preceding LT5575:	20 dB
Equivalent interference level at Rx input:	–118.7 dBm

The baseband second order product in this case is 17.5 dB below the thermal noise at the receiver input. The resulting degradation in sensitivity is <0.1 dB, so the receiver easily meets the specification of –115 dBm. This is illustrated in Figure 3.

Single WCDMA carriers can also appear out of band, as specified in section 7.5.1. These can be directly adjacent to the receive band at levels as high as –40 dBm.

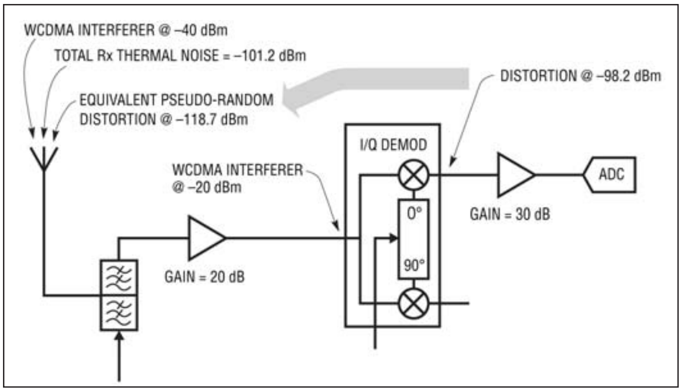

Figure 3 · 2nd order distortion due to WCDMA carrier.

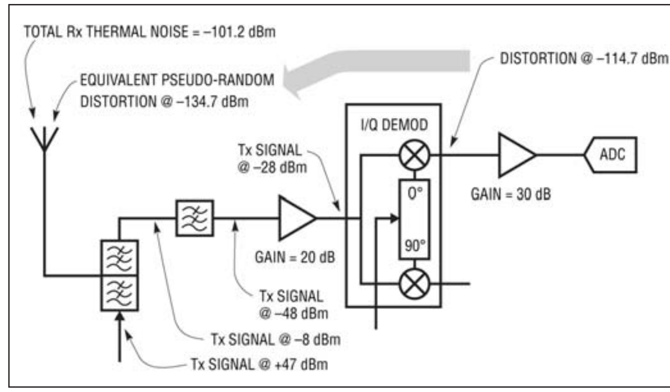

Figure 4 · Transmitter leakage effects.

Here again, the second order effect of such carriers upon sensitivity is negligible, as the preceding analysis shows.

Another threat to sensitivity comes from transmitter leakage in FDD systems, as shown in Figure 4. In an FDD system, the transmitter and receiver are operating at the same time. For the WCDMA Band I case, the transmit band is 130 MHz above the receive band. A single antenna is commonly used, with the transmitter and receiver joined by a diplexer. Here are some typical base station coupled resonator-type diplexer specifications:

Isolation, Tx to Rx 2110 MHz:	55 dB
Diplexer insertion loss, Tx path:	1.2 dB

In the case of a Wide Area base station, the transmit power may be as high as +46 dBm. At the transmit port of the diplexer the power will then be at least +47 dBm. Some portion of this high level modulated signal will leak to the receiver input and drive the I/Q demodulator:

Receiver input power:	–8 dBm
Rx BPF rejection @ 2110 MHz:	40 dB
RF gain preceding LT5575:	20 dB
Signal entering LT5575:	–28 dBm
LT5575 IIP_2, two tone:	+60 dBm
LT5575 a_2:	0.00317

A MATLAB simulation performed using a pseudo-random channel predicts the distortion at LT5575 output to be –114.7 dBm. Referring this signal back to the input:

RF gain preceding LT5575:	20 dB
Equivalent interference level at Rx input:	–134.7 dBm
Thermal noise at receiver input:	–101.2 dBm

This equivalent interference is 33.5 dB below the thermal noise at the receiver input. The resulting degradation in sensitivity is <0.1 dB, so the receiver easily meets the specification of –121 dBm.

Third Order Distortion (IP_3)

The third order intercept point (IP3) will have an effect upon the baseband signal when two properly spaced channels or signals enter the nonlinear element. Refer back to the transfer function:

$$y(t) = x(t) + a_2 x^2(\mathbf{t}) + a_3 x^3(t) + \ldots$$

where $x(t)$ is the input signal consisting of both desired and undesired signals. Consider now the third order distortion term. The coefficient a_3 is equal to $2/(3Z_o IP_3)$ where IP_3 is the single tone intercept point in watts. Note that the two-tone IP_3 is 4.78 dB below the single-tone IP_3.

Two signals entering the nonlinear element will generate a signal centered at zero frequency, if the spacing between the two signals is equal to the distance to zero frequency. Let $x(t) = A(t)\cos\omega t + B(t)\cos\omega_u t$, where the first term is the desired signal and the second term is an unwanted signal. The unwanted signal may be a tone or a modulated signal. If it is a tone, then $B(t)$ is simply a constant. If it is a modulated signal, then $B(t)$ represents the signal envelope. The output signal is then equal to $y(t)$:

$$\begin{aligned} y(t) &= A(t)\cos\omega t + \ldots + a_3(A(t)\cos\omega t + B(t)\cos\omega_u t)^3 + \ldots \\ &= A(t)\cos\omega t + \ldots + 3a_3A^2(t)B(t)\cos^2\omega t\cos\omega_u t + \\ &\quad 3a_3A(t)B^2(t)\cos\omega t\cos^2\omega_u t + \ldots \\ &= A(t)\cos\omega t + \ldots + (3/4)a_3A(t)B^2(t)\cos(2\omega_u - \omega)t + \ldots \end{aligned}$$

The third order distortion term of interest here is $(3/4)a_3A(t)B^2(t)\cos(2\omega_u - \omega)t$. In order for this distortion to appear at baseband, set $\omega = 2\omega_u$. The power of the distortion is $1/Z_o * E\{[(3/4)a_3A(t)B^2(t)]^2\}$, which can be expanded to:

$$P_{bb} = 9a_3^2/(16Z_o) * E\{A^2(t)\} * E\{B^4(t)\} \quad (7)$$

Consider the case of a modulated desired signal and a tone interferer; $B(t)$ may be replaced by B (see Figure 5). The value of $E\{B^4\}$ can be expressed as $(2Z_oP_u)^2$, where P_u

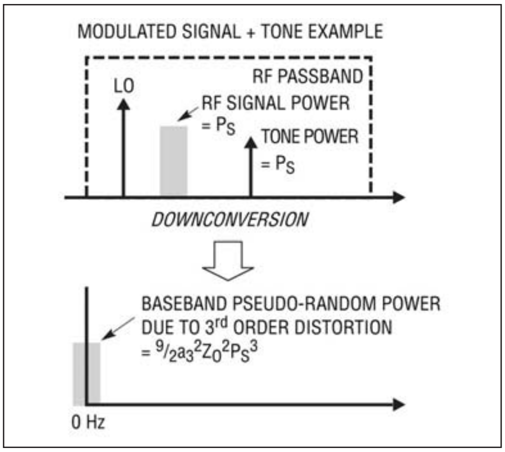

Figure 5 · Effects of 3rd order distortion.

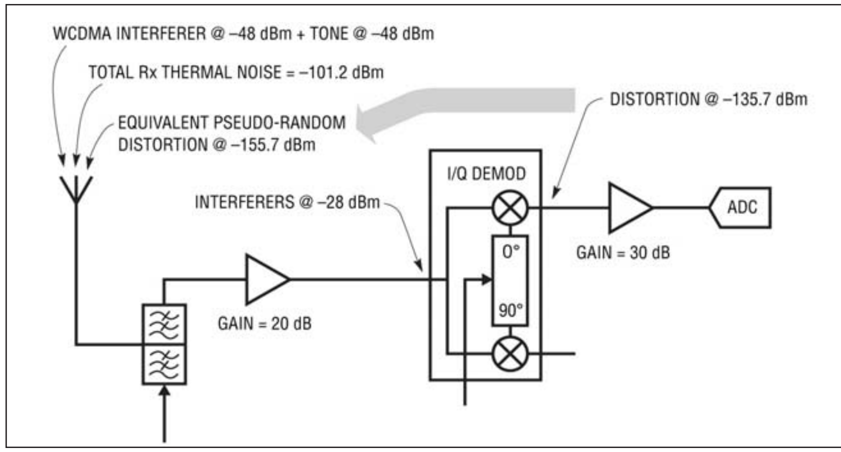

Figure 6 · 3rd order distortion due to WCDMA carrier + tone interferer.

is the power of the tone interferer. We can use Equation 2 to express $E\{A^2(t)\}$ in terms of the desired signal power as $2Z_oP_s$, where P_s is the power of the desired signal. The power level of the distortion at baseband is then:

$$P_{bb} = (9/2)P_sP_u^2Z_o^2a_3^2 \quad (8)$$

If the undesired signal is modulated, use Equations 2 and 5 to express $E\{B^4(t)\}$ as $3(2Z_oP_u)^2$, where P_u is the power of the tone interferer:

$$P_{bb} = (27/2)a_3^2Z_o^2P_sP_u^2 \quad (9)$$

In the direct conversion receiver example, Section 7.6.1 of the WCDMA specification calls for two interfering signals as shown in Figure 6.

One of these is a –48 dBm CW tone, and the other is a –48 dBm WCDMA carrier. These are offset in frequency so that the resulting 3rd order product appears centered about DC. Compute the intermodulation product generated in the I/Q demodulator:

RF gain preceding LT5575:	20 dB
Signals entering LT5575:	–28 dBm
LT5575 IIP_3, two tone:	+22.6 dBm
LT5575 a_3:	0.0244

A MATLAB simulation performed using a pseudo-random channel predicts the distortion at LT5575 output to be –135.8 dBm.

This result agrees well with the Equation 8, which predicts a distortion power of –135.7 dBm. Referring this signal back to the receiver input:

RF gain preceding LT5575:	20 dB
Equivalent interference level at Rx input:	–155.8 dBm
Thermal noise @ receiver input:	–101.2 dBm

The equivalent interference in this case is 54.6 dB below the thermal noise at the receiver input. The resulting degradation in sensitivity is <0.1 dB, so the receiver easily meets the specification of –121 dBm.

Conclusion

These calculations highlight the importance of 2nd and 3rd order linearity to a successful direct conversion receiver design. For a WCDMA application, 2nd order performance is critical for two reasons. First, there are CW tone interferers as high as –15 dBm entering the receiver. To minimize dynamic DC offset, the I/Q demodulator must present a 2nd order intercept point on the order of +40 dBm at the receiver input. Also, there are modulated interferers up to –40 dBm that can degrade the effective noise floor of the receiver if the 2nd order intercept point is not high enough. Leakage from the transmitter, which operates simultaneously with the receiver, can have the same effect.

The 3rd order linearity is less important, because interfering signals must be properly positioned to pose a threat to sensitivity. The WCDMA specification does require minimal degradation in sensitivity in the presence of a pair of –48 dBm interfering signals. In this case, if the 3rd order intercept point of the receiver is less than 0 dBm, there will be an appreciable loss of sensitivity.

Author Information

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