

# Understanding IP2 and IP3 Issues in Direct Conversion Receivers for WCDMA Wide Area Basestations

## Introduction

A 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 RF 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 much 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. 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. Also, a thorough understanding of the impact of the IP2 and IP3 issues is required. These parameters are critical to the overall performance of the receiver and the key component is the I/Q demodulator.

Unwanted baseband signals can be generated by 2nd order nonlinearity of the receiver. A tone at any frequency entering the receiver gives rise to a DC offset in the baseband circuits. Once generated, straightforward elimination of DC offset becomes very problematic. That is 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

by Doug Stuetzle

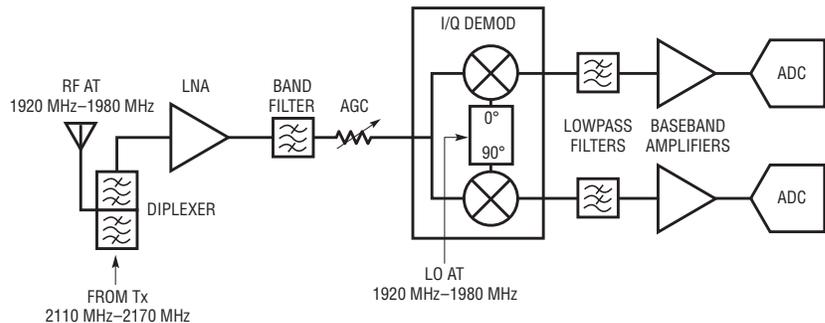


Figure 1. Direct conversion receiver architecture

effect of finite 2nd order linearity is critical.

Later in this article we 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 (IP2)

The second order intercept point (IP2) 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 2-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:

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

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

$$a_2 = \sqrt{\frac{2}{Z_0 IP2}}$$

where IP2 is the single tone intercept point in watts. Note that the 2-tone IP2 is 6dB below the single-tone IP2. The more linear the element, the smaller  $a_2$  is.

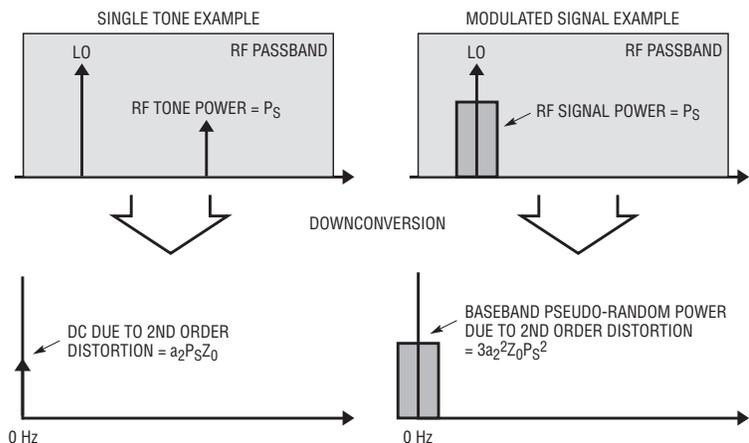


Figure 2. Effects of 2nd order distortion

Every signal entering the nonlinear element generates a signal centered at zero frequency. Even the desired signal gives 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

$$P_S = \frac{1}{Z_0} \cdot E\left\{[A(t)\cos\omega t]^2\right\}$$

where  $E\{\beta\}$  is the expected value of  $\beta$ . Since  $A(t)$  and  $\cos\omega t$  are statistically independent, we can expand  $E\{[A(t)\cos\omega t]^2\}$  as  $E\{A^2(t)\} \cdot E\{\cos^2\omega t\}$ . By trigonometry

$$P_S = \frac{1}{Z_0} \cdot E\{A^2(t)\} \cdot E\left\{\frac{1+\cos 2\omega t}{2}\right\}$$

The expected value of the second term is simply  $\frac{1}{2}$ , so the power of the desired signal simplifies to:

$$P_S = \frac{1}{2Z_0} \cdot E\{A^2(t)\} \quad [1]$$

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

$$P_S = \frac{A^2}{2Z_0}$$

In the more general case, the desired signal is digitally modulated by a pseudo-random data source. We can represent it as bandlimited 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:

$$E\{A^2(t)\} = 2Z_0P_S \quad [2]$$

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

$$\begin{aligned} y(t) &= A(t)\cos\omega t \\ &+ a_2[A(t)\cos\omega t]^2 \\ &+ \dots \text{Higher Order Terms} \\ &= A(t)\cos\omega t \\ &+ \frac{1}{2}a_2A^2(t) \\ &+ \frac{1}{2}a_2A^2(t)\cos 2\omega t \dots \end{aligned}$$

Consider the 2nd order distortion term  $\frac{1}{2}a_2[A(t)]^2$ . 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 is rejected by the baseband circuitry.

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

$$\text{DC OFFSET} = \frac{1}{2} \cdot a_2A^2 = a_2P_SZ_0 \quad [3]$$

If the desired signal is modulated, then the 2nd order result is a modulated baseband signal. The power of this term is

$$P_{BB} = \frac{1}{Z_0} \cdot E\left\{\left[\frac{1}{2}a_2A^2(t)\right]^2\right\}$$

This can be expanded to:

$$P_{BB} = \frac{(a_2)^2}{4Z_0} \cdot E\{A^4(t)\} \quad [4]$$

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:

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

The distortion power can then be expressed as

$$P_{BB} = \frac{3(a_2)^2}{4Z_0} \cdot [E\{A^2(t)\}]^2$$

Now express the expected value in terms of the desired signal power:

$$P_{BB} = 3(a_2)^2 Z_0 (P_S)^2 \quad [6]$$

It is the conversion of any given tone to DC, and any modulated signal into a baseband signal that makes 2nd 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 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.

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

$$\begin{aligned} &+ a_2[A(t)\cos\omega t + B(t)\cos\omega_u t]^2 \\ &+ \dots \text{Higher Order Terms} \end{aligned}$$

$$\begin{aligned} &= A(t)\cos\omega t \\ &+ \frac{1}{2}a_2A^2(t) + \frac{1}{2}a_2A^2(t)\cos 2\omega t \\ &+ 2a_2A(t)B(t)\cos\omega t \cos\omega_u t \dots \end{aligned}$$

$$\begin{aligned} &= A(t)\cos\omega t + \dots \\ &+ a_2A(t)B(t)\cos(\omega - \omega_u)t \dots \end{aligned}$$

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 includes a tone at the difference frequency. If the two

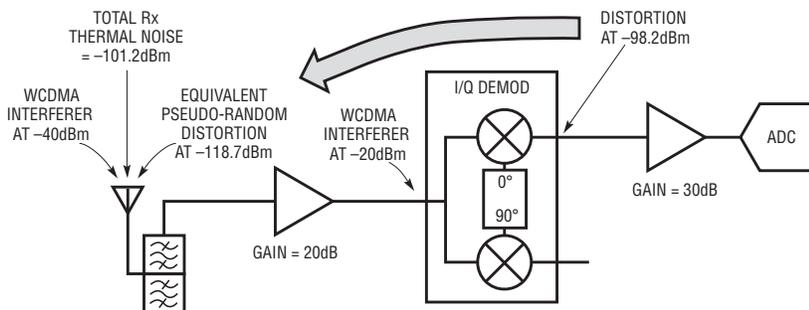


Figure 3. 2nd Order distortion due to WCDMA carrier

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 example. Figure 1 shows the block diagram of a typical WCDMA basestation receiver. Here are some key characteristics of this example:

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

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 below, the characteristics of the LT5575 I/Q demodulator as representative of a basestation class device of this type. Lowpass filters and baseband amplifiers bandlimit 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 is centered about DC and rejected by the demodulator. If there are two unwanted signals in the receive band (1960MHz, for example), then a second order product is generated by the LNA at the difference frequency. This signal is demodulated and appears 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 are not strong enough to create distortion products of any importance.

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

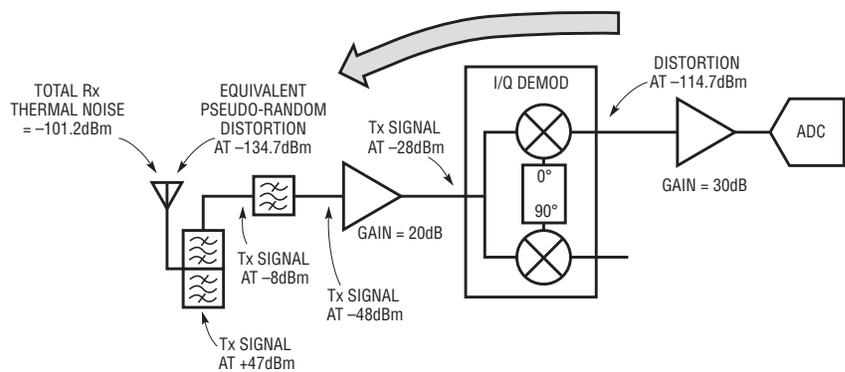


Figure 4. Transmitter leakage effects

2). As detailed above, this tone gives rise to a DC offset at the output of the demodulator. If the baseband cascade following the demodulator is DC-coupled, this offset is applied to the A/D converter, reducing its dynamic range. The WCDMA specification (3GPP TS 25104.740) calls out an out-of-band tone at  $-15\text{dBm}$ , located 20MHz 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:  $-15\text{dBm}$
- ❑ Diplexer rejection at 20MHz offset: 0dB
- ❑ Bandpass rejection at 20MHz offset: 2dB
- ❑ RF gain preceding LT5575: 20dB
- ❑ Tone entering LT5575: 3dBm
- ❑ LT5575 IIP2, 2-tone: 60dBm
- ❑ LT5575  $a_2$ : 0.00317
- ❑ DC offset at LT5575 output: 0.32mV
- ❑ Baseband voltage gain: 31.6
- ❑ DC offset at A/D input: 10mV

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 10MHz from the desired carrier, but is still in the receive band. The power level is  $-40\text{dBm}$ , and the receiver must meet a sensitivity of  $-115\text{dBm}$  for a 12.2kbps signal at a BER of 0.1%. Here are the details:

- ❑ Signal entering receive antenna port:  $-40\text{dBm}$
- ❑ RF gain preceding LT5575: 20dB
- ❑ Signal entering LT5575:  $-20\text{dBm}$
- ❑ LT5575 IIP2, 2-tone: 60dBm
- ❑ LT5575  $a_2$ : 0.00317

A MATLAB simulation performed using a pseudo-random channel

predicts a distortion at the LT5575 output of  $-98.7\text{dBm}$ . This result agrees well with that given by equation 6, which predicts a distortion power of  $-98.2\text{dBm}$ .

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:  $-121\text{dBm}$
- ❑ Processing + coding gain: 25dB
- ❑ Signal to noise ratio at sensitivity: 5.2dB
- ❑ Thermal noise at receiver input:  $-101.2\text{dBm}$

Now refer the distortion signal back to the receiver input:

- ❑ RF gain preceding LT5575: 20dB
- ❑ Equivalent interference level at Rx input:  $-118.7\text{dBm}$

The baseband second order product in this case is 17.5dB below the thermal noise at the receiver input. The resulting degradation in sensitivity is  $<0.1\text{dB}$ , so the receiver easily meets the specification of  $-115\text{dBm}$ . 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  $-40\text{dBm}$ . 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 130MHz above the receive band. A single antenna is commonly used, with the transmitter and receiver joined by a diplexer. Here are some typical basestation coupled resonator-type diplexer specifications:

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

In the case of a Wide Area basestation, the transmit power may be as high as 46dBm. At the transmit port of the diplexer the power is at least 47dBm. This high level modulated signal leaks to the receiver input, and some portion of it drives the I/Q demodulator:

- ❑ Receiver input power: -8dBm
- ❑ Rx BPF rejection at 2110MHz: 40dB
- ❑ RF gain preceding LT5575: 20dB
- ❑ Signal entering LT5575: -28dBm
- ❑ LT5575 IIP2, 2-tone: 60dBm
- ❑ LT5575  $a_2$ : 0.00317

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

- ❑ Distortion at LT5575 output: -114.7dBm

Refer this signal back to the receiver input:

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

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

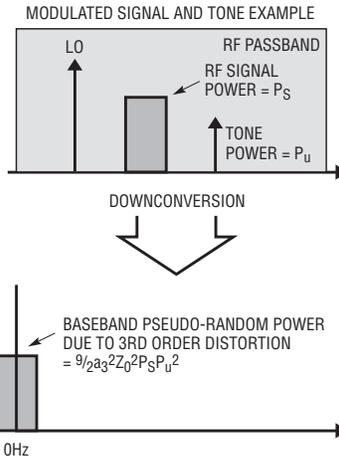


Figure 5. Effects of 3rd order distortion

### Third Order Distortion (IP3)

The third order intercept point (IP3) has an effect upon the baseband signal when two properly spaced channels or signals enter the nonlinear element.

Refer back to the transfer function:  $y(t) = x(t) + a_2x^2(t) + a_3x^3(t) + \dots$ , 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  $2/(3Z_0IP3)$  where IP3 is the single tone intercept point in Watts. Note that the 2-tone IP3 is 4.78dB below the single-tone IP3.

Two signals entering the nonlinear element 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  $y(t)$ :

$$y(t) = A(t)\cos\omega t + \dots + a_3 [A(t)\cos\omega t + B(t)\cos\omega_u t]^3 + \dots \text{Higher Order Terms}$$

$$= A(t)\cos\omega t + \dots + 3a_3A^2(t)B(t)\cos^2\omega t \cos\omega_u t + 3a_3A(t)B^2(t)\cos\omega t \cos^2\omega_u t \dots$$

$$= A(t)\cos\omega t + \dots + \frac{3}{4}a_3A(t)B^2(t)\cos(2\omega_u - \omega)t \dots$$

The third order distortion term of interest here is  $\frac{3}{4}a_3A(t)B^2(t)\cos(2\omega_u - \omega)t$ . In order for this distortion to appear at baseband, set  $\omega = 2\omega_u$ . The power of the distortion is

$$P_{BB} = \frac{1}{Z_0} \cdot E \left\{ \left[ \frac{3}{4} a_3 A(t) B^2(t) \right]^2 \right\}$$

which can be expanded to

$$P_{BB} = \frac{9(a_3)^2}{16Z_0} \cdot E \{ A^2(t) \} \cdot E \{ B^4(t) \} \quad [7]$$

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  $(2Z_0P_u)^2$ , where  $P_u$  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  $2Z_0P_s$ , where  $P_s$  is the power of the desired signal. The power level of the distortion at baseband is then:

$$P_{BB} = \frac{9}{2} \cdot P_s (P_u)^2 (Z_0)^2 (a_3)^2 \quad [8]$$

If the undesired signal is modulated, use Equations 2 and 5 to express  $E\{B^4(t)\}$  as  $3(2Z_0P_u)^2$ , where  $P_u$  is the power of the tone interferer:

$$P_{BB} = \frac{27}{2} \cdot (a_3)^2 (Z_0)^2 P_s (P_u)^2 \quad [9]$$

In the direct conversion receiver example, Section 7.6.1 of the WCDMA specification calls for two interfering

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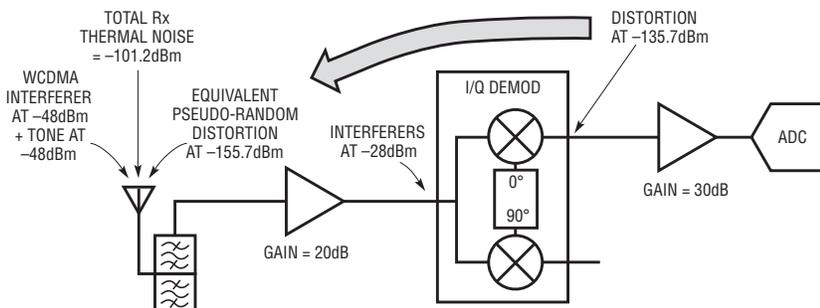


Figure 6. 3rd Order distortion due to WCDMA carrier + tone interferer

can protect the rectifier diodes from excessive reverse voltage and can prevent pulse-skipping by limiting the minimum duty cycle. Both of these lockouts shut off all four regulators when tripped.

These functions are realized with a pair of built in comparators at inputs UVLO and OVLO. A resistor divider from the VINSW pin to each comparator input sets the trip voltage and hysteresis. The VINSW pin pulls up to  $V_{IN1}$  when any RUN pin is pulled high, and is open when all three RUN pins are low. This reduces shutdown current by disconnecting the resistor dividers from the input voltage. These comparators have a 1.2V threshold and also have 10 $\mu$ A of hysteresis. The UVLO hysteresis is a current sink while the OVLO hysteresis is a current source. UVLO should be connected to VINSW and OVLO connected to ground if these functions aren't used.

### Frequency Control

The switching frequency is set by a single resistor to the  $R_T$ /SYNC pin. The value is adjustable from 250kHz to 2.5MHz. Higher frequencies allow smaller inductors and capacitors, but efficiency is lower and the supply has a smaller allowable range of step-down ratios due to the minimum on and off time constraints.

The frequency can also be synchronized to an external clock by connecting it to the  $R_T$ /SYNC pin. The clock source must supply a clock signal

whenever the LT3507 is powered up. This leads to a dilemma if the clock source is to be powered from one of the LT3507 regulators: there is no clock until the regulator comes up, but the regulator won't come up until there's a clock! This situation is easily overcome with a capacitor, a low leakage diode and a couple of resistors. The capacitor isolates the clock source from the  $R_T$ /SYNC pin until the power is up and the resistor on the  $R_T$ /SYNC pin sets the initial clock frequency. The application in Figure 1 shows how this is done.

### Typical Application

Figure 1 shows a typical LT3507 application. This application allows a very wide input range, from 6V to 36V. It generates four outputs: 5V, 3.3V, 2.5V and 1.8V. Efficiencies for three of the outputs are shown in Figure 2. The LDO produces a particularly low noise output at 2.5V, as shown in Figure 3.

The outputs are set to coincident tracking using the 5V supply as the

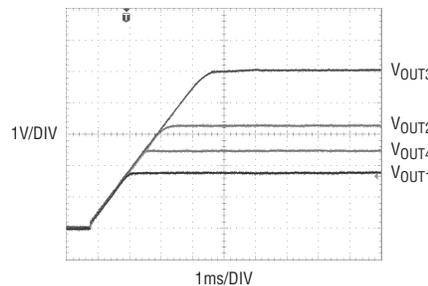


Figure 4. Coincident tracking waveforms

master. But wait, there's no resistor divider on the TRK/SS4 pin! It's no mistake; the LDO output coincidentally tracks the supply it's sourced from (the 3.3V supply in this case) as long as Q1 is a low  $V_{CESAT}$  transistor, such as the NSS30101 used here. Just remember that this little cheat only works for coincident tracking. Figure 4 shows the start-up waveforms of the four outputs.

In this application, the clock is synchronized to an external source that is powered from the 3.3V output. A capacitor isolates the clock until the 3.3V supply is good, and then passes the clock signal to the  $R_T$ /SYNC pin. It should be noted that the LDO can actually supply up to 0.5A as long as  $I_{OUT4} + I_{OUT2} \leq 1.5A$ .

### Conclusion

The LT3507 provides a compact solution for four power supplies. Its tiny 5mm  $\times$  7mm QFN package includes three highly efficient switching regulators and a low dropout linear regulator. Just a few small inductors and ceramic capacitors are needed to create four high efficiency step-down regulators. Plenty of options insure that the LT3507 meets the needs of a wide variety of multiple output applications. 

Authors can be contacted  
at (408) 432-1900

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signals as shown in Figure 6. One of these is a -48dBm CW tone, and the other is a -48dBm 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: 20dB
- Signals entering LT5575: -28dBm
- LT5575 IIP3, 2-tone: 22.6dBm
- LT5575  $a_3$ : 0.0244

A MATLAB simulation performed using a pseudo-random channel pre-

dicts distortion at LT5575 output of -135.8dBm. This result agrees well with the equation 8, which predicts a distortion power of -135.7dBm.

Refer this signal back to the receiver input:

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

The equivalent interference in this case is 54.6dB below the thermal noise at the receiver input. The resulting

degradation in sensitivity is <0.1dB, so the receiver easily meets the specification of -121dBm.

### Conclusion

The calculations given here using the LT5575 I/Q demodulator show that a WCDMA wide area basestation receiver can be successfully implemented using a direct conversion architecture. The high 2nd order linearity and input 1dB compression point of the LT5575 are critical to meeting the performance requirements of such a design. 