

Effective IM2 products estimation for two-tone and W-CDMA modulated blockers in 3GPP direct-conversion receivers

As third-generation (3G) wireless networks are currently expanding in Japan (IMT-2000), Europe (UMTS), and the US (cdma2000), the need for low-cost, low-power consumption, and low form-factor user equipment (UE) is becoming important for the commercial development of 3G mobile handsets. The direct-conversion receiver architecture, with the proper use of silicon processes, circuit design techniques, and architecture implementation, represents a promising system solution for highly integrated platforms for 3G handsets. In this article, we present a commercially available, fully integrated, zero-IF receiver solution for 3G radios (Figure 1). The receiver-input, second-order intercept point (IIP2) requirement is discussed extensively in this paper, as it is

a key specification for a direct-conversion receiver. Measurements, simulations, and calculations are presented specifically on this topic.

The direct-conversion receiver architecture

As seen in Figure 1, direct-conversion or zero-IF receiver architecture enables the pathway for a full on-chip integration of the receiver. This is because the signal is directly demodulated to baseband I and Q signals. In a 3G, W-CDMA FDD (full-duplex) operation mode, only an external duplexer is needed for separation between Rx and Tx sections. Furthermore, the post-LNA RF filter is required in a FDD radio to reject out-of-band blockers and transmitter leakage at demodulator input. This happens due to finite duplexer Tx-Rx isolation. In a zero-IF receiver IC, channel selectivity is achieved at baseband by on-chip, low-pass filters. Following the channel filtering, I/Q signals at baseband are amplified by variable-gain amplifiers (VGAs) before they get digitized in the analog baseband section of the radio modem IC. Design considerations for direct-conversion receivers have been studied thoroughly [1, 2].

In *Second-order distortion effects*, we present and discuss all critical sources leading to the generation of second-order nonlinearity products in the zero-IF, receiver-IC downconverter. In *IIP2 derivation*, we provide a detailed review of the second-order, input-intercept point (IIP2) derivation. Then, in the last two sections, we tackle specifically the estimation of true IM2 products and the

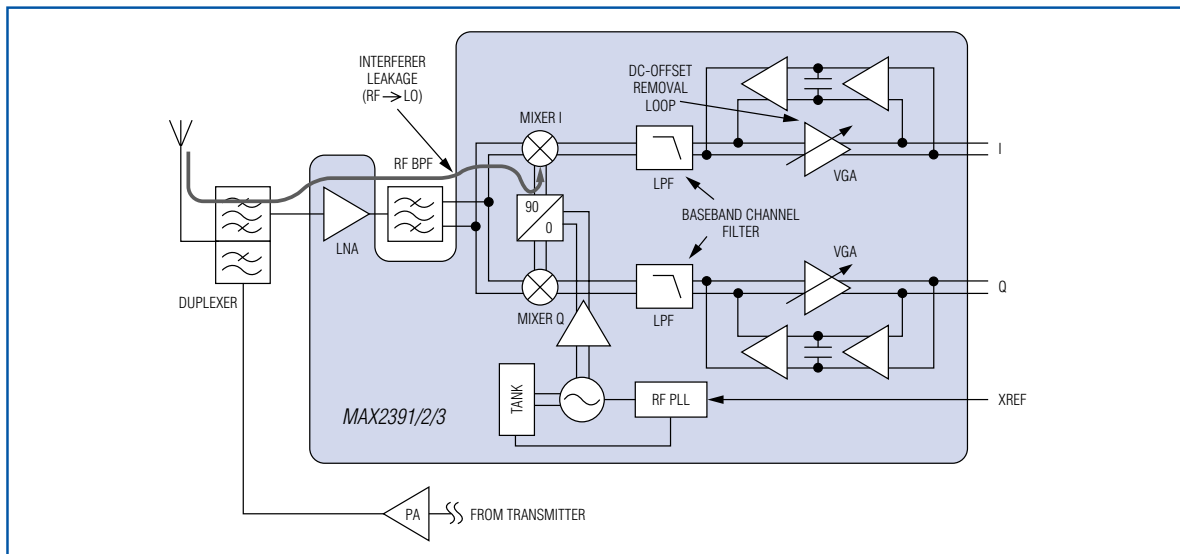


Figure 1. This direct-conversion receiver IC is a fully integrated, zero-IF receiver solution for 3GPP, FDD handset radios.

minimum IIP2 requirements for a 3GPP zero-IF receiver, based on the specified 3G standard test cases [3].

Second-order distortion effects

In a zero-IF receiver, second-order intermodulation products (IM2) have been shown to present a problematic source of interference [1]. Care must be taken to minimize the level of these products in the receiver's baseband channel. In a zero-IF receiver, the front-end, second-order nonlinearity demodulates the AM components of an amplitude-modulated blocker down to baseband. These second-order IM2 products consist of the squared version of the blocker envelope. Therefore, the bandwidth of these undesirable spectral components at baseband can be up to twice the bandwidth of the blocker's amplitude envelope. Depending on the desired signal modulation bandwidth at baseband, these IM2 products contribute partially, or fully to the degradation of the overall receiver's jamming margin.

The IM2 distortion products we are discussing here are those which occur in the downconverter section of a zero-IF receiver. This is because the low-frequency IM2 products in the LNA are normally filtered out by AC-coupling or bandpass filtering between the LNA and the mixer blocks. There are many different mechanisms responsible for the generation of IM2 products in a zero-IF receiver [4]. However, it is important to present here the two main IM2 generation mechanisms.

RF self-mixing

RF self-mixing occurs because of the imperfect, hard-switching I-V characteristic of the commutating stage in a zero-IF receiver mixer, and because the RF signal is leaking into the LO port due to parasitic coupling. The imperfect hard switching happens in a mixer when it is driven with low LO powers and, therefore, it behaves more like a linear multiplier. As a result, in the presence of an RF-to-LO leakage component at the LO port (Figure 1), the zero-IF mixer's output contains a signal that is proportional to both the square of the input signal and the RF-to-LO coupling factor. Consequently, second-order IM products are generated at baseband. When RF signal leaking to the LO port is a strong blocker, this is quite detrimental to receiver performance.

Downconverter RF-stage, second-order nonlinearity and LO-stage, switching-pairs mismatches

Upon the introduction of a strong CW or modulated blocker at the I/Q mixer inputs in a zero-IF receiver, the

second-order nonlinearity in the active devices of the mixer transistor or RF stage generates low-frequency IM2 products. These products, along with the desired RF signal and the blocker, are part of the transistor-stage output currents. In a perfectly balanced mixer, including perfectly matched mixer loads or devices in the switching pairs or LO stage, the equivalent differential IM2 products are translated to high frequencies. Also, the equivalent common-mode IM2 products are canceled out at the mixer differential output. However, in addition to the deviation of the LO duty cycle from 50%, the mismatches that exist in the LO-stage devices result in a direct low-frequency leakage gain that is presented to the low-frequency IM2 products. As a result, these products get translated to I/Q mixers' baseband outputs.

It is important to note that previously we assumed that the downconverter section in a zero-IF receiver is the main limiting block in IM2 product suppression. This is true if the baseband stages following the I/Q mixers have high common-mode suppression (>60dB).

IIP2 derivation

The weakly nonlinear characteristics of a receiver front-end can be presented as:

$$V_o(t) = a_1 \times V_i(t) + a_2 \times V_i(t)^2 + L \quad (\text{Eq 1})$$

To express the second-order input intercept point (IIP2) based on two-tone derivation, the input signal to the receiver in **Figure 2** is expressed as $V_i(t) = A \times \cos(\omega_1 t) + A \times \cos(\omega_2 t)$, with a total two-tone power equal to A^2/R . The second-order distortion products at the receiver front-end are derived as:

$$a_2 \times V_i(t)^2 = a_2 \times A^2 \times [1 + \cos((\omega_1 - \omega_2)t) + \cos((\omega_1 + \omega_2)t) + (\cos(2\omega_1 t)/2) + (\cos(2\omega_2 t)/2)] \quad (\text{Eq 2})$$

The resultant output IM2 products at $(f_1 + f_2)$ and $(f_1 - f_2)$, including the resulting DC offset, are expressed as:

$$a_2 \times A^2 \times [1 + \cos((\omega_1 - \omega_2)t) + \cos((\omega_1 + \omega_2)t)] \quad (\text{Eq 3})$$

The total power in the equation 3 output IM2 products, referred to as system impedance (R), is calculated as:

$$|a_2|^2 \times A^4 \times \left(\frac{1}{R} + \frac{1}{2R} + \frac{1}{2R} \right) = 2 \times |a_2|^2 \times \frac{A^4}{R} \quad (\text{Eq 4})$$

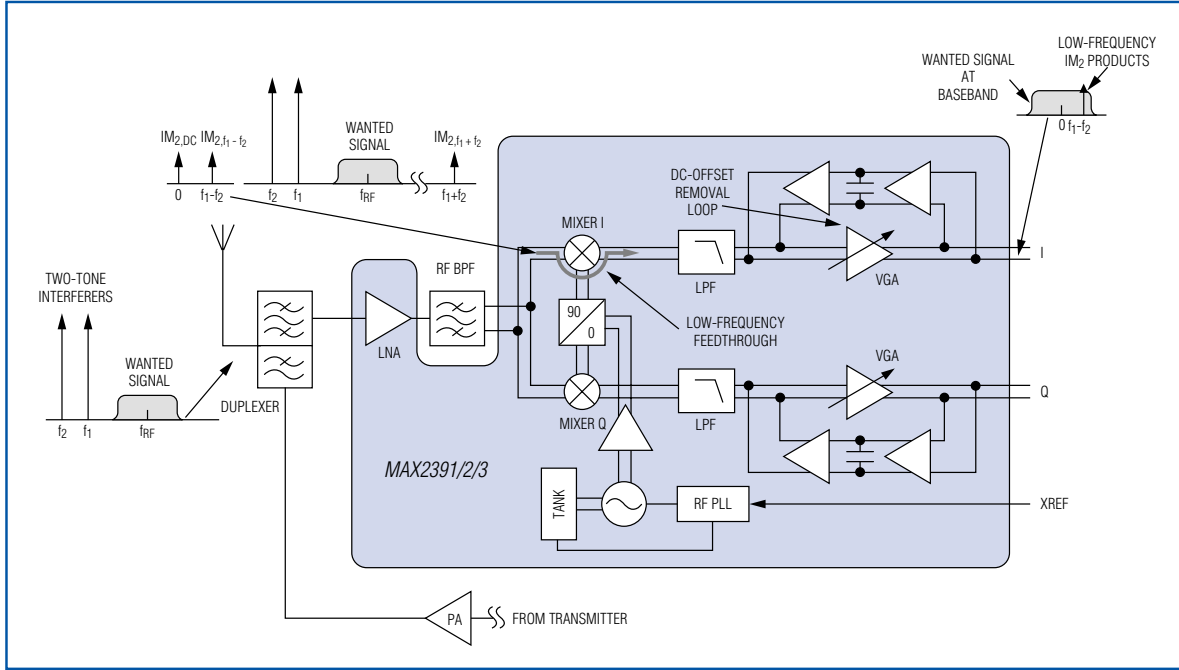


Figure 2. Second-order intermodulation distortion occurs due to the two-tone blocker in the zero-IF receiver.

At the IIP2 power level, the total input signal power is defined as equal to the total power in the output IM2 products (equation 4) after being referred to the input. This is done through dividing by the gain factor, $|a_1|^2$. As a result, we can write that:

$$A_{IIP2}^2/R = 2 \times \left| \frac{a_2}{a_1} \right|^2 \times \frac{A_{IIP2}^4}{R} \Rightarrow \quad (\text{Eq 5})$$

$$IIP2 = IIP2^2 / \left[\left| \frac{a_1}{a_2} \right|^2 \times \frac{1}{2R} \right] \Rightarrow$$

$$IIP2 = \left| \frac{a_1}{a_2} \right|^2 \times \frac{1}{2R}$$

Based on a total two-tone input power equal to $P_{2T} = A^2/R$, the total power level of the IM2 products (equation 4) referred to the receiver input can be expressed as:

$$P_{IM2} = 2 \times \left| \frac{a_2}{a_1} \right|^2 \times \frac{A^4}{R} = \frac{P_{2T}^2}{IIP2} \Rightarrow \quad (\text{Eq 6})$$

$$P_{IM2}(\text{dBm}) = 2 \times P_{2T}(\text{dBm}) - IIP2(\text{dBm})$$

It is important to note that in equation 4 the resulting IM2 products' total power level is composed of 50% (-3dB) IM2 product at DC, 25% (-6dB) IM2 product at $(f_1 - f_2)$, and 25% (-6dB) IM2 product at $(f_1 + f_2)$. Therefore, the power level of the IM2 product at $(f_1 - f_2)$

can be derived from equations 4 and 6 as:

$$P_{IM2,(f_1-f_2)}(\text{dbm}) = 2 \times P_{2T} - IIP2 - 6\text{dB} \Rightarrow$$

$$P_{IM2,(f_1-f_2)}(\text{dBm}) = 2 \times P_{1T}(\text{dBm}) - IIP2(\text{dBm}) \quad (\text{Eq 7})$$

where power level per tone (P_{1T} at f_1 or f_2) is 50% of the total two-tone power, $P_{1T}(\text{dBm}) = P_{2T}(\text{dBm}) - 3\text{dB}$.

Effective, low-frequency IM2 products

In a 3GPP W-CDMA radio, the worst-case interferers at receiver input are not two-tone type, but wideband digitally modulated-type blockers. Therefore, to derive the required receiver IIP2 for a certain desired BER performance, it is important to estimate the effective low-frequency IM2 products based on a modulated blocker. It is also necessary to understand the nature of the modulated blocker, specifically its nonconstant envelope. This is because the envelope gets stripped off the RF blocker in the front-end, second-order nonlinearity and gets translated to baseband with a squared version of the envelope. The two major modulated blockers in a 3GPP W-CDMA receiver are presented in 3G standard test cases, 7.3.1 and 7.6.1 [3]. The first test case, 7.3.1, specifies the minimum required sensitivity for $BER < 10^{-3}$, while the transmitted uplink signal (UL) is at maximum power level (+24dBm) at the antenna. The second test

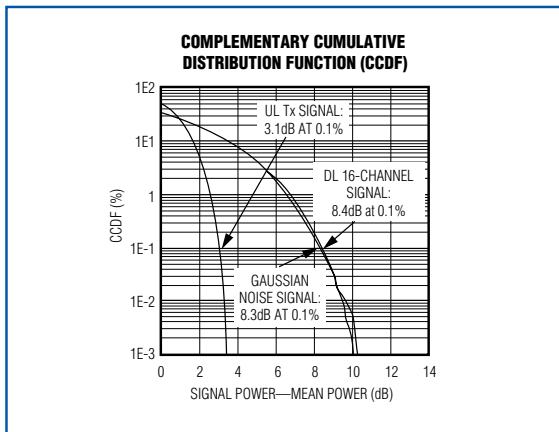


Figure 3. CCDFs of a UL reference channel and a DL 16-channel blocker are compared to Gaussian noise signal CCDF.

case, 7.6.1, specifies the minimum-required receive-signal level at the antenna connector for $BER < 10^{-3}$ in the presence of a modulated downlink (DL) -44dBm blocker. This is at 15MHz offset from the desired signal, while the transmitted UL power at the antenna is +20dBm.

The UL-reference measurement channel (12.2kbps) structure, which represents the transmitted uplink signal at the antenna of a 3G W-CDMA handset, is described in table A.1 of the 3GPP standard document [3]. It consists of a dedicated physical-data channel (DPDCH) and a dedicated physical-control channel (DPCCH). In the radio modem section, both DPDCH and DPCCH channels are spread to 3.84Mcps, scaled to the appropriate power ratio (DPCCH/DPDCH = -5.46dB), HPSK scrambled, and filtered by a 1.92MHz root-raised-

cosine (RRC) filter with roll-off factor $\alpha = 0.22$ [5]. Conversely, the forward-channel modulated blocker at 15MHz offset from the desired channel consists of the common channels needed for tests (Table C.7 in [3]) and 16 dedicated data channels (Table C.6 in [3]). The signal is QPSK encoded, spread to 3.84Mcps, complex scrambled, and filtered by a RRC filter similar to that used for UL signal [5]. Both signals have a -3dB bandwidth equal to 3.84MHz at RF, and 99% of total signal power is within a bandwidth of 4.12MHz (-6dB BW). To understand the nature of the envelope of either the modulated UL-transmitted (Tx) signal or the modulated DL 16-channel signal, and to estimate the effective IM2 products due to each one of them in a W-CDMA receiver, it is important to study first the power statistics of each signal. It is also essential to estimate the effective IM2 products as they each exist in a W-CDMA zero-IF receiver. This is represented by the complementary cumulative-distribution function (CCDF) that provides the signal's peak-average power ratio (PAR) vs. probability. Figure 3 shows ADS™-simulated CCDFs of the UL-transmitted signal and the DL 16-channel signal as compared to the CCDF of a Gaussian noise signal.

It is worth noting from Figure 3 that the PAR at 0.1% probability of the UL-reference channel, based on one transmitted DPDCH, is equal to 3.1dB. On the other hand, the DL blocker at the 15MHz offset, which contains 16 dedicated traffic channels, has an 8.4dB PAR at 0.1% that is almost equal to that of a Gaussian noise signal. It will be shown later that the effective, low-frequency IM2 product estimation differs between the two standard test

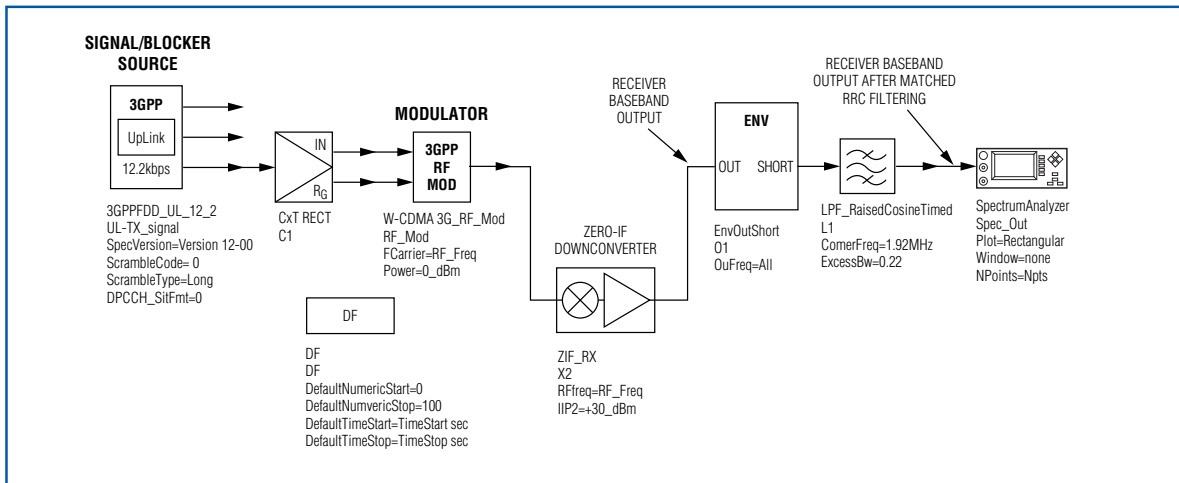


Figure 4. An ADS template details IM2 products estimation.

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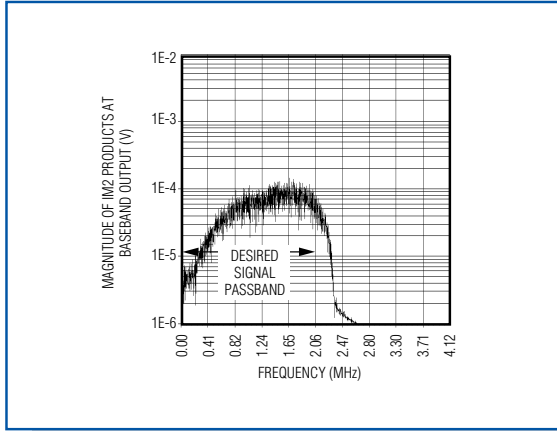


Figure 5. Simulated RRC-filtered IM2 products at zero-IF receiver output are produced due to an UL Tx blocker.

cases. This is because of the PAR discrepancy between the two different blockers.

An ADS IM2 simulation template was created to investigate the IM2 products due to a modulated blocker at the input of a W-CDMA zero-IF receiver (Figure 4). The IM2 products were filtered by an RRC filter, which is matched to the base station transmitter RRC filter. The resulting low-frequency IM2 products were measured in simulation with the 0Hz to 2.06MHz desired signal bandwidth at baseband, which is half the signal's 99% power BW at RF.

In Figures 5 and 6, simulated IM2 product magnitude spectrums at the baseband output of a zero-IF downconverter (after matched RRC filtering) is presented for both the W-CDMA UL reference measurement channel (12.2kbps) and for the W-CDMA DL 16-channel blocker, respectively. In the ADS template and for simulation purposes only, we used a modulated blocker power equal to 0dBm and a zero-IF downconverter IIP2 equal to +30dBm. The resulting low-frequency IM2-product power level for a 0dBm, W-CDMA UL Tx signal, integrated over the desired signal passband of 1kHz to 2.06MHz, is equal to -43.7dBm. In addition, the DC offset due to second-order nonlinearity is equal to 5mV, which is equivalent to -33dBm into 50W (Figure 5). On the other hand, the resulting IM2 products' power level for a 0dBm, W-CDMA DL 16-channel blocker, integrated over the desired signal passband of 1kHz to 2.06MHz, is equal to -33.1dBm. The resulting DC offset due to second-order nonlinearity is also equal to 5mV (Figure 6).

Returning to equation 6 and assuming a total power level for a two-tone blocker of 0dBm at zero-IF downconverter

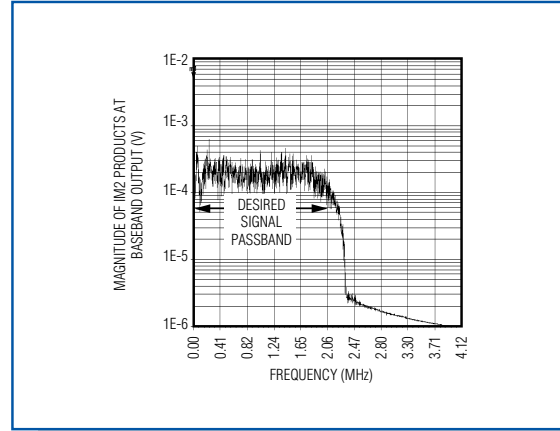


Figure 6. Simulated RRC-filtered IM2 products at zero-IF receiver output occur due to a DL 16-channel blocker.

input, the total IM2-product power level referred to receiver input is calculated as $P_{IM2}(dBm) = 2 \times P_{2T}(dBm) - IIP_2(dBm) = -30dBm$. The resulting DC-offset level is -33dBm and the power level of the IM2 product at $(f_1 - f_2)$ is -36dBm, based on equations 4 and 7, respectively. Therefore, it can be concluded that the integrated, low-frequency, IM2-product power level over the 1kHz to 2.06MHz band, due to a 0dBm, UL Tx blocker, is 7.7dB lower than the low-frequency, $(f_1 - f_2)$, IM2-product power level due to a two-tone 0dBm blocker. Similarly, the equivalent total low-frequency IM2 products' power level due to a 0dBm DL 16-channel blocker is 2.9dB higher than the low-frequency, $(f_1 - f_2)$, IM2-product power level due to a 0dBm two-tone blocker. The total effective IM2-product power levels based on the previous results are summarized in the following equations:

For the UL reference channel or Tx-blocker case,

$$P_{IM2,UL_TX}(dBm) = \quad (Eq 8)$$

$$2 \times P_{UL_TX}(dBm) - IIP2(dBm) - 13.7dB =$$

$$2 \times P_{1T}(dBm) - IIP2(dBm) - 7.7dB$$

For the DL 16-channel blocker case,

$$P_{IM2,DL_16Ch}(dBm) = \quad (Eq 9)$$

$$2 \times P_{DL_16Ch}(dBm) - IIP2(dBm) - 3.1dB =$$

$$2 \times P_{1T}(dBm) - IIP2(dBm) + 2.9dB$$

In equations 8 and 9, the power level per tone (P_{1T} at f_1 or f_2) is 50% of the total power level (P_{2T}) of a two-tone blocker having the same power level as the modulated blocker, $P_{1T}(dBm) = P_{2T}(dBm) - 3dB = P_{UL_TX/DS_16Ch}(dBm) - 3dB$. It is important to note that the -13.7dB reduction

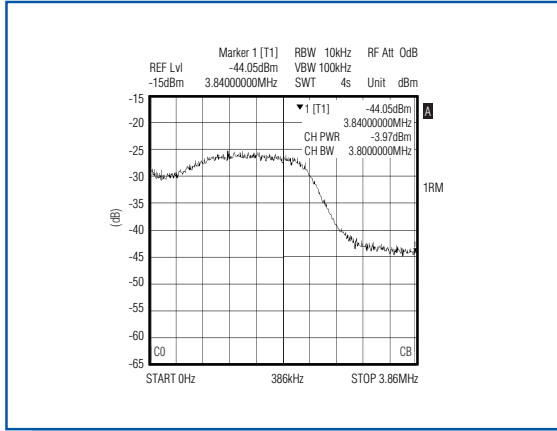


Figure 7. Measured IM2 products, without RRC filtering, at zero-IF receiver output transpire due to an UL Tx blocker.

factor relative to the total IM2-product level estimate in equation 8 is very similar to the factor obtained in the results presented in reference [6]. Furthermore, the results presented by equation 8 have been verified through lab measurements done on a zero-IF receiver device with the part shown in Figure 1. The measured IM2 products at baseband due to UL Tx blocker (Figure 7) show similar spectrum characteristics to the simulated IM2 products shown in Figure 5. The measured spectrum components close to DC in **Figure 7** are larger than the corresponding simulated components in Figure 5. This is due to the additional downconverted phase noise close to DC in the actual measured zero-IF receiver.

Minimum IIP2 requirements for a W-CDMA receiver

In the following section, the required minimum IIP2 for a W-CDMA, zero-IF receiver for both test cases, 7.3.1 and 7.6.1, is derived based on equations 8 and 9, respectively. All IIP2 calculations are done in reference to the receiver LNA input.

3GPP standard test case 7.3.1

- In FDD mode, the estimated maximum UL Tx signal leakage at the LNA input is -24dBm ($P_{UL_TX, LNA} = P_A \text{ power at duplexer} - \text{Duplexer_Isolation}_{TX_RX}$, min = +26dBm - 50dB = -24dBm). The worst-case insertion loss (IL) of the duplexer before the LNA is assumed equal to -2dB. In a 3GPP, IMT-band radio handset, the Tx-leakage frequency offset relative to the desired Rx signal frequency is 190MHz.
- It was shown in [7] that, for a required traffic-channel sensitivity of -117dBm/3.84MHz, the required minimum

E_b/N_t is 7dB after decoding and despreading of the desired traffic channel. In test case 7.3.1, which specifies the minimum required traffic-channel sensitivity for $BER < 10^{-3}$, N_t is assumed to be purely noise (N_O) due to receiver NF. For a chip rate of 3.84Mcps and a user bit rate of 12.2kbps, the processing gain is $G_p = 10\log(3.84\text{Mcps}/12.2\text{kbps}) = 25\text{dB}$. We can calculate that the maximum allowable noise power (P_N) due to receiver NF is $P_N = P_{\text{Sensitivity}} + G_p - E_b/N_t = -117\text{dBm} + 25\text{dB} - 7\text{dB} = -99\text{dBm}$.

- At minimum sensitivity level, it is required that the low-frequency IM2 products due to UL Tx-leakage blocker do not desensitize the receiver. The resulting DC offset due to IIP2 has no effect because, in a W-CDMA zero-IF receiver, DC offsets are typically rejected on-chip. If it is assumed that the total power level of low-frequency IM2 products needs to be at least 11dB lower than P_N (maximum of 0.3dB receiver desensitization), the maximum allowable input IM2 due to UL Tx-leakage blocker, referred to receiver LNA input, can be estimated using: $P_{IM2,UL_TX} = P_N - 11\text{dB} - I_{L\text{duplexer}} \leq -99\text{dBm} - 11\text{dB} - 2\text{dB} = -112\text{dBm}$.
- The receiver IIP2,TX at Tx offset (190MHz), referred to receiver LNA input, is calculated using equation 8: $P_{IM2,UL_TX}(\text{dBm}) = 2 \times P_{UL_TX,LNA}(\text{dBm}) - IIP_{2,TX}(\text{dBm}) - 13.7\text{dB} \Rightarrow IIP_{2,TX}(\text{dBm}) \geq +50\text{dBm}$.

3GPP standard test case 7.6.1

- In this test case, the desired signal is 3dB above the minimum sensitivity specified in test case 7.3.1. Hence, the maximum allowable noise plus interference power level is -96dBm. This is 3dB higher than level calculated in the previous test case. Assuming the same level of receiver noise (-99dBm), the maximum-allowable interference power level is -96dBm - 3dB = -99dBm.
- The total interference power due to the W-CDMA DL, 16-channel blocker, 15MHz offset from the desired signal is assumed to be divided mainly between three products. These are phase-noise reciprocal mixing (25% or -6dB), blocker level at receiver output after on-chip filtering (25% or -6dB), and low-frequency IM2 products due to this blocker (50% or -3dB). Hence, we can estimate the maximum allowable input IM2 products' level due to DL blocker, referred to receiver LNA input, using: $P_{IM2,DL,16Ch} = P_N - 3\text{dB} - I_{L\text{duplexer}} \leq -99\text{dBm} - 3\text{dB} - 2\text{dB} = -104\text{dBm}$. The low-frequency IM2 products due to the UL Tx-leakage signal have been neglected, because the UL Tx power in this test has been reduced by 4dB relative to the level specified in test case 7.3.1.

- In this test case, the specified modulated blocker level is equal to -44dBm at antenna; hence, with -2dB IL in duplexer, the level of the blocker at LNA input, $P_{DL_16Ch, LNA}$, is -46dBm.

- The receiver IIP2 (15MHz) at 15MHz offset, referred to receiver LNA input, is calculated using equation 9:
$$P_{IM2, DS_16Ch}(\text{dBm}) = 2 \times P_{DL_16Ch, LNA}(\text{dBm}) - IPP_{2, (15MHz)}(\text{dBm}) - 3.1\text{dB} \Rightarrow IPP_{2, (15MHz)}(\text{dBm}) \geq +9\text{dBm}.$$

When all are referred to LNA input, it is noteworthy that the required zero-IF receiver IIP2 (TX) at the UL Tx frequency offset is higher than the required IIP2 (15MHz) at the DL 16-channel blocker frequency offset. When translating the IIP2 (TX) requirement to the I/Q mixers inputs, this imposes the need for mixers' IIP2 (I/Q_mixer) to be larger than +60dBm. However, this requirement can be relaxed by the use of the post-LNA filter, which provides selectivity at the Tx-leakage offset frequency [8].

Conclusion

This article presented simulations, calculations, and measurements to estimate the required zero-IF receiver IIP2 in the presence of a modulated W-CDMA blocker. Depending on the envelope nature of the modulated blocker, it has been shown that the resulting low-frequency IM2 products' level at baseband can be lower or higher than the low-frequency IM2 beat-tone level that results from an equivalent two-tone blocker.

A similar article appeared in the April, 2004 issue of RF Design.

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