Keywords: rf, rf design, radio frequency, RF, Intercept point, IP, intermodulation, IM, continuous wave, CW, IIP2, IIP3, IM, IIM3, carrier-to-interference ratio, C/I

TUTORIAL 749

Use Selectivity to Improve Receiver Intercept Point

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Abstract: A receiver's intermodulation (IM) spurious response attenuation is a measure of the receiver's ability to receive a modulated-input RF signal frequency on its assigned channel frequency in the presence of two interfering continuous wave (CW) tones. The receiver's protection against spurious response interference is a measure of the its ability to discriminate between the input signal at the assigned frequency and an undesired signal at any other frequency to which it is responsive. This application note analyzes the sources of RF interference that affect receiver linearity. A dual-conversion receiver is examined for off-channel interference response.

A similar version of this article appeared in the December 1997 issue of *RF Design* magazine.

Click here for an overview of the wireless components used in a typical radio transceiver.

Introduction

A receiver's second- and third-order intercept points (IPs) represent the two most important linearity specifications for a radio circuit or system. The intercept points allow us to predict the receiver's intermodulation (IM) performance, which describes the radio's susceptibility to interference from adjacent or nearby users. This article presents a modification of the traditional receiver intercept point cascading equation for both the second- and third-order IM cases. The mathematical derivation for each of the second-order (IP2) and third-order (IP3) intercept point cascading equations incorporates the effect of adding selectivity (S) between receiver stages to improve IIP2 and IIP3.

Note: in this article all variables in uppercase letters refer to dB or dBm units and all variables in lowercase letters refer to linear units.

Spurious Response Interference

In wireless specifications related to the recommended minimum performance standards for the mobile station, the receiver's IM performance is specified technically under two main topics: the receiver's IM spurious response attenuation, and the receiver's protection against spurious response interference.

The IM spurious response attenuation is a measure of the receiver's ability to receive a modulated-input RF signal frequency on its assigned channel frequency in the presence of two interfering continuous-wave (CW) tones. These tones are separated from the assigned input signal frequency so that the nth-order mixing of the two undesired signals can occur in the nonlinear elements of the receiver, thereby producing a third signal in the band of the desired signal. The receiver's protection against spurious response interference is a measure of its ability to discriminate between the input signal at the assigned frequency and an undesired signal at any other frequency to which it is responsive.

Interference from Third-Order IM Products

As a result of third-order mixing in a receiver's front-end, two off-channel CW tones at frequencies f_1 and f_2 introduce a third-order IM product at a frequency equal to ($2f_1$ - f_2), which can appear in the on-channel signal passband (**Figure 1a**). This in-band third-order intermodulation (IM3) product reduces the carrier-to-interference ratio (C/I) at the receiver's demodulator. Based on a linear 3:1 slope (**Figure 1b**), the level of this input IM3 product (IIM3, in dBm) can be determined using an equation that includes the receiver's overall input IP3 (IIP3, in dBm) and the input power level of each of the two off-channel CW tones (P_I, in dBm):[1]

$$IIM3 = 3 \times P_I - 2 \times IIP3 \text{ (dBm)} \qquad \text{(Eq. 1)}$$

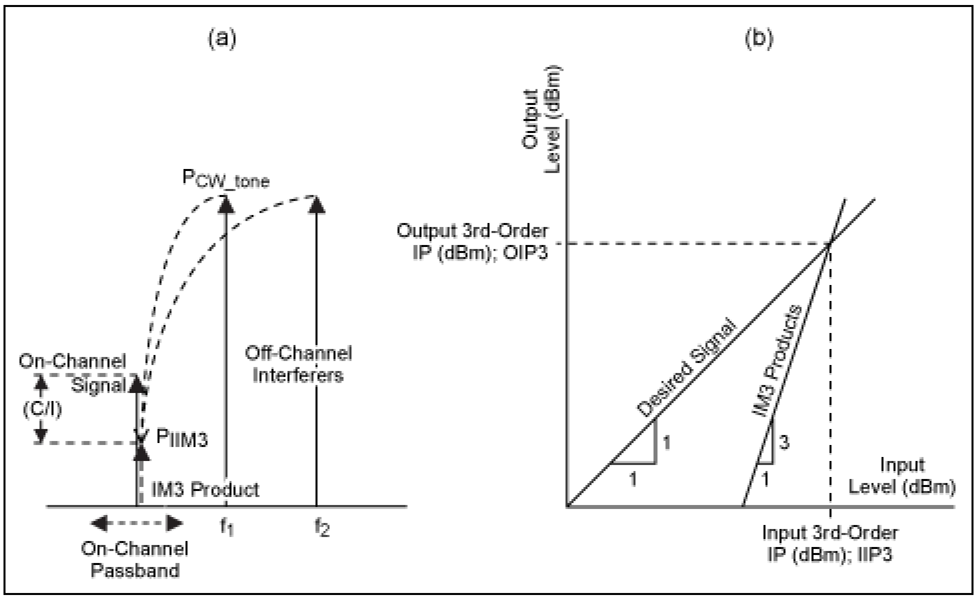

Figure 1. IM3 product as an in-band interferer due to two off-channel CW tones (a), and third-order intercept point (IP) definition (b).

Figure 2 represents a conventional dual-conversion superheterodyne receiver architecture. In this type of receiver architecture, the IM3 products from the off-channel CW interferers are generated in the low-noise amplifier (LNA), the first mixer, the IF amplifier, the second mixer, and the IF limiting amplifier. All the IM3 products merge at the demodulator input, resulting in an equivalent in-band IM3 product at the receiver input (IIM3). This IM3 product, acting as an in-band interferer, can be reduced by minimizing the IM3 contribution from the IF amplifier, the second mixer, and the IF limiting amplifier. The IM3 contribution is reduced by introducing a certain amount of IF selectivity (S) to these off-channel interferers in the IF filter following the first mixer (IF filter 1). Note that filter selectivity (S) refers to the attenuation in the IF filter 1 rejection band at the off-channel interferers' frequencies relative to the on-channel filter passband insertion loss (IL). Thus, the total rejection (R) (in dB) in the IF filter stopband at the off-channel CW tones' frequencies can be defined as: R = -(IL + S). The IF filter selectivity (S) reduces the third-order distortion and dynamic range requirements of the subsequent receiver blocks. As a result, the overall receiver's IIP3 can be optimized in order to minimize the equivalent in-band IIM3 product and thus meet the required receiver baseband (C/I) ratio.

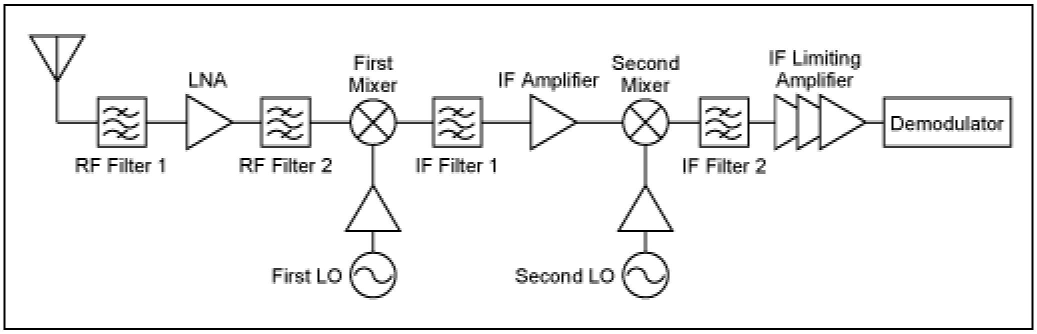

Figure 2. Conventional superheterodyne dual-conversion receiver.

Modified Third-Order Input Intercept Point (IIP3) Cascading Equation

In **Figure 3** the dual-conversion receiver architecture (Figure 2) is divided into three blocks: the RF block, the IF filter 1, and the IF block. The RF block, or block 1, consists of the receiver RF stages preceding the first IF filter. The IF block, or block 2, consists of the receiver's IF stages following the first IF filter. Block 1 has a gain, G_1, at RF and an equivalent third-order input intercept point $IIP3_1$. Block 2 has a gain, G_2, at IF and an equivalent third-order input intercept point $IIP3_2$. The power level of each of the two off-channel CW interferers present at the receiver's input is assumed to equal P_I, which is the level of the two off-channel CW tones' input to block 1. P_2 is the level of the two off-channel CW tones translated to IF and input to block 2. IIM3 is the total IM3 distortion power from the two off-channel CW tones that is referred to the receiver input. $IIM3_1$ is the total IM3 distortion power generated in block 1 that is referred to its input. $IIM3_2$ is the total IM3 distortion power generated in block 2 that is referred to its input.

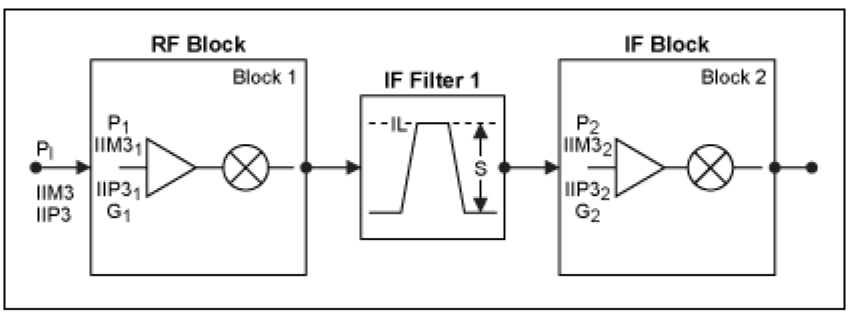

Figure 3. Block diagram for deriving the modified IP3 cascading equation. The equation incorporates the effect of adding selectivity (S) to receiver stages at the two off-channel CW tones' frequencies. Power symbols are in dBm, and gain is in dB.

In the following derivation the input IM3 distortion voltage of block 1 and the input IM3 distortion voltage of block 2, divided by the voltage gain of preceding stages, are added exactly in-phase as a worst-case condition. In this way we obtain the total IM3 distortion voltage that is referred to the receiver input. Assuming a system characteristic impedance of 1Ω, we can write the following:

$$\sqrt{iim3} = \sqrt{iim3_1} + \sqrt{(iim3_2/(g_1/il))} \text{ (volts)} \qquad \text{(Eq. 2)}$$

Where the square root converts the IM3 powers to voltages. The terms iim3, $iim3_1$, and $iim3_2$ are in linear power units (watts or milliwatts). Also, G_1 (dB) = 10 × $\log_{10}(g_1)$ and IL (dB) = 10 × $\log_{10}$(il).

Equation 1 can be rearranged into the following equation:

$$IIP3 = P_I + ½(P_I - IIM3)\ (dBm) \qquad (Eq.\ 3)$$

Equation 3 defines the input IP3 for the whole receiver, and can be rewritten in linear power units (milliwatts, or mW) instead of dBm:

$$p_I/iip3 = \sqrt{(iim3/p_I)} \qquad (Eq.\ 4)$$

Similar to what we did in equation 3, we can define $IIP3_1$ and $IIP3_2$ for block 1 and block 2, respectively, as:

$$IIP3_1 = P_1 + ½(P_1 - IIM3_1)\ (dBm) \qquad (Eq.\ 5)$$

$$IIP3_2 = P_2 + ½(P_2 - IIM3_2)\ (dBm) \qquad (Eq.\ 6)$$

Knowing that $P_1(dBm) = P_I$ and $P_2(dBm) = P_I + (G_1 - IL - S)$, we obtain from equations 5 and 6:

$$IIP3_1 = P_I + ½(P_I - IIM3_1)\ (dBm) \qquad (Eq.\ 7)$$

$$IIP3_2 = (P_I + G_1 - IL - S) + ½(P_I + G_1 - IL - S - IIM3_2)\ (dBm) \qquad (Eq.\ 8)$$

As we have done for equation 3, equations 7 and 8 can be rewritten in linear power units instead of dBm to result in equations 9 and 10, respectively:

$$p_I/iip3_1 = \sqrt{(iim3_1/p_I)} \qquad (Eq.\ 9)$$

$$p_I(g_1/il)/(iip3_2 \times s^{3/2}) = \sqrt{iim3_2/((g_1/il)p_I)} \qquad (Eq.\ 10)$$

Where $S(dB) = 10 \times \log_{10}(s)$ and $IL(dB) = 10 \times \log_{10}(il)$. Note that S(dB) and IL(dB) are positive numbers.

Returning to equation 2 and dividing it by $(p_I)^{1/2}$, we get equation 11:

$$\sqrt{(iim3/p_I)} = \sqrt{(iim3_1/p_I)} + \sqrt{(iim3_2/(g_1/il)p_I} \qquad (Eq.\ 11)$$

If we substitute each term in equation 11 by equivalent terms using equations 4, 9, and 10, and after simplifying by removing the term p_I, we obtain the following modified IIP3 cascading equation:

$$1/iip3 = 1/iip3_1 + (g_1/il)/(iip3_2 \times s^{3/2}) \qquad (Eq.\ 12)$$

As we can see from equation 12, by choosing a highly selective IF filter (s >> 1), we can minimize the effect of the IF block input IP3 ($IIP3_2$) on the overall receiver input IP3 (IIP3), which becomes almost defined by the RF block IIP3 ($IIP3_1$). It is worth noting that in a cascaded system analysis the IF block input IP3 ($IIP3_2$) should be replaced with an equivalent input IP3. This exchange effectively introduces selectivity ahead of the IF block. This equivalent $IIP3_2$ can be written as:

$$IIP3^e{}_2 = IIP3_2 + (3/2) \times S\ (dBm) \qquad (Eq.\ 13)$$

A more generalized equation that predicts the overall input IP3 of a receiver chain with M cascaded stages can be formulized based on equation 12. Each stage has a linear gain (g_n), an input IP3 ($IIP3_n$, in watts), and a selectivity (s_n) at the two off-channel CW tones' frequencies. Together this introduces an in-band IM3 product (assuming that $il_n << s_n$):

$$1/iip3 = 1/iip3_1 + (g_1/(iip3_2 \times s_1^{3/2}) + (g_1 \times g_2)/(iip3_3 \times (s_1 \times s_2)^{3/2}) + ... + (g_1 \times g_2 ... g_{M-1})/(iip3_M \times (s_1 \times s_2 ... s_{M-1})^{3/2}) \quad \text{(Eq. 14)}$$

Where $S_n(dB) = 10 \times \log_{10}(s_n)$. Note that this equation simplifies the classic equation for the intercept point calculation of a cascade of M stages when setting s_n to 1. This translates into setting selectivity S_n to 0dB.[1]

Interference from Second-Order IM Products

Receiver spurious responses are frequencies that differ from the on-channel RF signal frequency, yet they still produce an output interferer in the receiver passband if encountered at a sufficiently high level. One of these spurious response frequencies is at the half-IF frequency. This half-IF spurious response results in a second-order IM product (IM2), which occurs in the receiver's RF front-end. The IM2 level can be predicted from the second-order intercept point (IP2) of the receiver's RF front-end, which is defined up to and including the first mixer in the receiver chain (Figure 2).

For high-side injection in the first mixer (**Figure 4a**), a CW tone at the receiver's input, which is offset from the LO frequency by $-f_{IF}/2$, is downconverted to IF by the $(-2.f_{CW} + 2.f_{LO})$ IM product that occurs in the first mixer.[1,2] Similarly for low-side injection, a CW tone, which is offset from the LO frequency by $+f_{IF}/2$, is downconverted to IF by the $(2.f_{CW} - 2.f_{LO})$ IM product. Based on a linear 2:1 slope (**Figure 4b**), the level of this input IM2 product (IIM2, in dBm) can be determined using an equation that includes the receiver's RF front-end input IP2 (IIP2, in dBm) and the power level of the input half-IF CW tone (P_I, in dBm):[1]

$$IIM2 = 2 \times P_I - IIP2 \text{ (dBm)} \quad \text{(Eq. 15)}$$

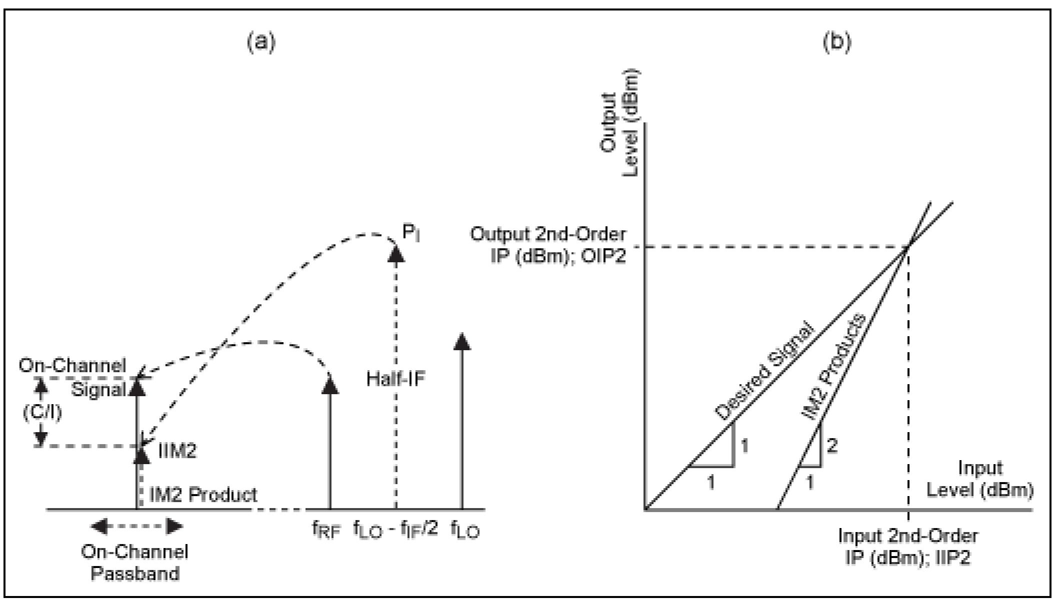

Figure 4. IM2 product as an in-band interferer due to half-IF spurious response (a), and second-order

intercept point (IP) definition (b).

This in-band IM2 product from the half-IF spurious response can be reduced by minimizing the second-order IM contribution from the first mixer. This is done by introducing a certain amount of RF selectivity (S) to this off-channel interferer in the RF filters preceding the first mixer (RF filters 1 and 2). Note that filter selectivity (S) refers to the attenuation in the RF filter rejection band at the spurious response frequency relative to the on-channel filter passband insertion loss (IL). The RF filter selectivity (S) reduces the second-order distortion and dynamic-range requirements of the first mixer. As a result, the overall receiver's RF front-end IIP2 can be optimized to minimize the equivalent in-band IIM2 product from the half-IF tone, thus meeting the required receiver baseband (C/I) ratio.

Modified Second-Order Input Intercept Point (IIP2) Cascading Equation

In **Figure 5**, the dual-conversion receiver RF front-end is divided into three blocks: RF filter 2, block 1 (which consists of all stages preceding RF filter 2), and block 2 (which follows RF filter 2 and includes the first mixer). Block 1 has a gain, G_1, at RF and an equivalent second-order input intercept point $IIP2_1$. Block 2 has a gain, G_2, at RF and an equivalent second-order input intercept point $IIP2_2$. The power level of each half-IF CW tone present at the receiver's input is assumed to be equal to P_I, which is the level of the half-IF CW tone input to block 1. P_2 is the level of the half-IF CW tone input to block 2. IIM2 is the total IM2 distortion power from the half-IF CW tone that is referred to the receiver input. $IIM2_1$ is the total IM2 distortion power generated in block 1 that is referred to its input. $IIM2_2$ is the total IM2 distortion power generated in block 2 that is referred to its input.

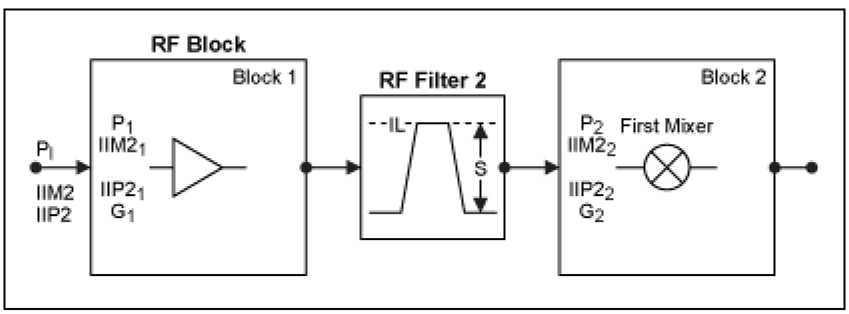

Figure 5. Block diagram for deriving the modified IP2 cascading equation, which incorporates the effect of adding RF selectivity (S) to the receiver's RF front-end stages at the half-IF spurious frequency. Power symbols are in dBm, and gain is in dB.

In the following derivation the input IM2 distortion voltage of block 1 and the input IM2 distortion voltage of block 2, divided by the voltage gain of preceding stages, are added exactly in-phase as a worst-case condition. In this way we obtain the total IM2 distortion voltage that is referred to the receiver's input. Assuming a system characteristic impedance of 1Ω, we can write the following:

$$\sqrt{iim2} = \sqrt{iim2_1} + \sqrt{(iim2_2/(g_1/il))} \text{ (volts)} \quad \text{(Eq. 16)}$$

Where the square root converts the IIM2 powers to voltages. The terms iim2, $iim2_1$, and $iim2_2$ are in linear power units (watts or milliwatts). Also, G_1 (dB) = 10 × $\log_{10}$(g1) and IL (dB) = 10 × $\log_{10}$(il).

Equation 15 can be rearranged into the following equation:

$$IIP2 = P_I + (P_I - IIM2) \text{ (dBm)} \quad \text{(Eq. 17)}$$

Equation 17 defines the input IP2 for the whole receiver, and can be rewritten in linear power units (milliwatts, or mW) instead of dBm:

$$p_I/iip2 = iim2/p_I \quad \text{(Eq. 18)}$$

Similar to what we did with equation 17, we can define $IIP2_1$ and $IIP2_2$ for block 1 and block 2, respectively, as:

$$IIP2_1 = P_1 + (P_1 - IIM2_1)\ \text{(dBm)} \quad \text{(Eq. 19)}$$

$$IIP2_2 = P_2 + (P_2 - IIM2_2)\ \text{(dBm)} \quad \text{(Eq. 20)}$$

Knowing that $P_1(\text{dBm}) = P_I$ and $P_2(\text{dBm}) = P_I + (G_1 - IL - S)$, we obtain from equations 19 and 20:

$$IIP2_1 = P_I + (P_I - IIM2_1)\ \text{(dBm)} \quad \text{(Eq. 21)}$$

$$IIP2_2 = (P_I + G_1 - IL - S) + (P_I + G_1 - IL - S - IIM2_2)\ \text{(dBm)} \quad \text{(Eq. 22)}$$

As we have done for equation 17, equations 21 and 22 can be rewritten in linear power units instead of dBm to result in equations 23 and 24, respectively:

$$p_I/iip2_I = iim2_I/p_I \quad \text{(Eq. 23)}$$

$$(p_I \times (g_1/il))/(iip2_2 \times S^2) = iim2_2/(g_1/il) \times p_I) \quad \text{(Eq. 24)}$$

Where $S(\text{dB}) = 10 \times \log_{10}(s)$ and $IL(\text{dB}) = 10 \times \log_{10}(il)$. Note that S(dB) and IL(dB) are positive numbers.

Returning to equation 16 and dividing it by $(p_I)^{1/2}$,we get equation 25:

$$\sqrt{(iim2/p_I)} = \sqrt{(iim2_I/p_I)} + \sqrt{(iim2_2/(g_1/il) \times p_I)} \quad \text{(Eq. 25)}$$

If we substitute each term in equation 25 by equivalent terms using equations 18, 23, and 24, and after simplifying by removing the term p_I, we obtain the following modified IIP2 cascading equation:

$$\sqrt{(1/iip2)} = \sqrt{(1/iip2_I)} + \sqrt{((g_1/il)/(iip2_2 \times s^2)} \quad \text{(Eq. 26)}$$

As we can see from equation 12, by choosing a highly selective RF filter ($s >> 1$), we can minimize the effect of the first mixer-block input IP2 ($IIP2_2$) on the overall receiver RF front-end input IP2 (IIP2). It is worth noting that in a cascaded system analysis the first mixer-block input IP2 ($IIP2_2$) should be replaced with an equivalent input IP2. This exchange effectively introduces selectivity in the RF filter. This equivalent $IIP2_2$ can be written as:

$$IIP2^e{}_2 = IIP2_2 + 2 \times S\ \text{(dBm)} \quad \text{(Eq. 27)}$$

A more generalized equation to predict the overall input IP2 of a receiver's RF front-end chain with M cascaded stages can be formulized based on equation 26. Each stage has a linear gain (g_n), an input IP2 ($iip2_n$, in watts), and a selectivity (s_n) at the half-IF CW tone frequency. This introduces an in-band IM2 product (assuming that $il_n << s_n$):

$$\sqrt{1/iip2} = \sqrt{1/iip2_1} + \sqrt{g_1/(iip2_2 \times s_1^2)} + \sqrt{(g_1 \times g_2)/(iip2_3 \times (s_1 \times s_2)^2)} + ... + \sqrt{(g_1 \times g_2 ... g_{M-1})/(iip2_M \times (s_1 \times s_2 ... s_{M-1})^2)} \quad \text{(Eq. 28)}$$

Where $S_n(dB) = 10 \times \log_{10}(s_n)$.

References

1. S. Maas, *Microwave Mixers*, Norwood, MA, Artech House, 1993.
2. P. Vizmuller, *RF Design Guide*, Norwood, MA, Artech House, 1995.

Related Parts		
MAX1470	315MHz Low-Power, +3V Superheterodyne Receiver	Free Samples
MAX2338	Triple/Dual-Mode CDMA LNA/Mixers	
MAX2410	Low-Cost RF Up/Downconverter with LNA and PA Driver	Free Samples
MAX2538	Quadruple-Mode PCS/Cellular/GPS LNA/Mixers	