A Simplified Approximation Method for Cascaded System Adjacent and Alternative Channel Power Ratio

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This article presents a simple approximation method by which the cascaded system performance for adjacent channel power ratio (ACPR) and alternate channel power ratio (ALT) of a linear transmitter can be predicted from the performance of the various component stages. The allowable ACPR and ALT for each stage can then be allocated so that the overall design meets the required system specifications.

Introduction

ACPR and ALT are two critical requirements for certain wireless transmitters. These specifications determine the amount of interference to neighboring channels caused by power leaking into the adjacent spectrum. These requirements also ensure that the transmitted waveform will suffer minimal distortion due to nonlinearties in the transmitter channel.

Basic assumptions

The method described in this article is based on the following approximations, which are valid in most cases:

- The ACPR requirements of the wireless standard are much higher than the ACPR of an ideal modulated signal without distortion. For example, the ACPR of an ideal quadrature phase shift keying (QPSK) signal in wideband code-division multiple access (WCDMA) is about –55 dBc from the vector signal generator. The ACPR specification by standard is –33 dBc.
- The random noise level is considerably lower than the distortion level.

These two assumptions imply that the ACPR and ALT performance of a transmitter is determined entirely by the severity of nonlinear distortion.

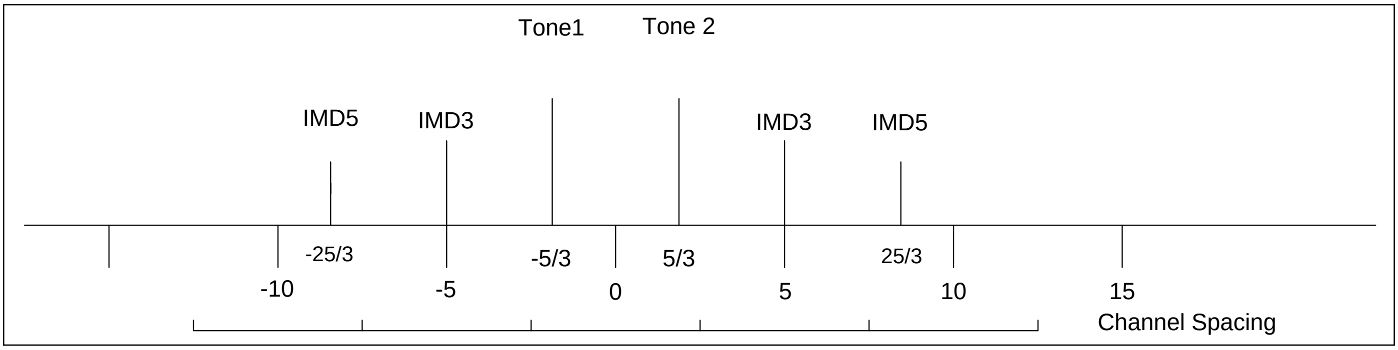
Multi-tone and two-tone approximation

Any bandwidth-limited signal can be sampled in the time domain by the Nyquist sampling rate, which is twice the signal bandwidth without information loss. In a similar fashion, any time-limited signal with duration T can be sampled in the frequency domain at the rate of 1/(2T) (hertz per sample), which in turn can be fully recovered by a time domain window with duration T. When T increases sufficiently, the time domain alias diminishes and can be neglected.

Therefore, a modulated signal — similar to what is used for WCDMA — can be thought of as the sum of very many narrow tones, each occupying a tiny piece of modulation spectrum. When this collection of tones is passed through a nonlinear amplifier, some ACP will occur due to spectral regrowth. This can be thought of as the result of each of the discrete tones described above “intermoding” with each of the other tones.

To simplify the measurement of the nonlinear distortion for transmitter components, a two-tone approximation is often used, with the level of each tone set to be 3 dB lower than the signal channel power level. The two tones are spaced symmetrically away from the carrier frequency and separated by half of the channel bandwidth. Therefore, the IMD3 and IMD5 products fall into the center of the adjacent and alternative channels, respectively.

An example for WCDMA channel spacing is shown in Figure 1.



▲ **Figure 1. Two-tone approximation.**

ACPR of a cascaded system

For a single stage, the ACPR can be approximated by

$$[ACPR] = [OIMD3] - [P_{out}] - [C] \quad dB \qquad (1)$$

where square brackets represent the logarithm in dB and dBm, $OIMD3$ is the output third-order intermodulation product and P_{out} is the output power level. $[C]$ is a constant ~= 8 dB in WCDMA modulation.

Unless otherwise specified, all variables in this article without square brackets represent decimal numbers (as opposed to logarithms). Equation (1) in decimal form is therefore:

$$C * ACPR = \frac{OIMD3}{P_{out}} \qquad (2)$$

The right side of the equation is often referred to as "intermodulation ratio" and is widely used to derive the cascaded $OIMD3$ product, cascaded intermodulation ratio and cascaded IIP3 and OIP3. The value of $[C]$ depends on the spectral properties of the modulated waveform and, therefore, differs from standard to standard.

The following derivation of cascade ACPR results in two slightly different formulas, depending upon whether or not the intermodulation products of each stage are correlated. If they are correlated, the multi-stage total output intermodulation ratio is accumulated for each stage in voltage, (see Equation (3)), where V represents voltage, G represents voltage gain and the subscripts are the stage numbers. Using Equation (2) in Equation (3), the cascade ACPR is shown in Equation (4).

If the intermodulation products of each stage are uncorrelated, the output intermodulation products will be added in power (see Equation (5)), where K is the power gain of each stage.

Using Equation (2) in Equation (5), the cascade ACPR is:

$$\frac{VOIM3_{cascade}}{VPout_{cascade}} = \frac{G_2G_3 \ldots G_n VOIM3_1 + G_3 \ldots G_n VOIM3_2 + \ldots + VOIM3_n}{VPout_{cascade}} = \frac{VOIM3_1}{VPout_1} + \frac{VOIM3_2}{VPout_2} + \ldots + \frac{VOIM3_n}{VPout_n}$$

▲ **Equation (3)**

$$\sqrt{C_{cascade} ACPR_{cascade}} = \sqrt{C_1 ACPR_1} + \sqrt{C_2 ACPR_2} + \ldots + \sqrt{C_n ACPR_n}$$

▲ **Equation (4).**

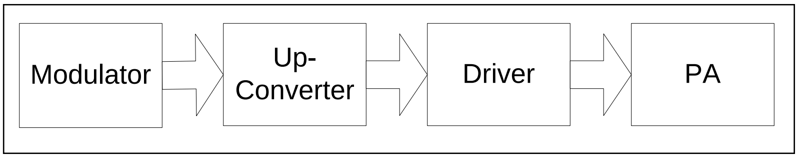
$$\frac{OIM3_{cascade}}{Pout_{cascade}} = \frac{K_2K_3 \ldots K_n OIM3_1 + K_3 \ldots K_n OIM3_2 + \ldots + OIM3_n}{Pout_{cascade}} = \frac{OIM3_1}{Pout_1} + \frac{OIM3_2}{Pout_2} + \ldots + \frac{OIM3_n}{Pout_n}$$

▲ **Equation (5).**

$$C_{cascade} ACPR_{cascade} = C_1 ACPR_1 + C_2 ACPR_2 + \ldots + C_n ACPR_n \qquad (6)$$

If we assume that the coefficients (C_s) are the same for all stages, the calculation can be simplified. The measurement results described later in this article indicate that this is a correct assumption. In the following discussion, a constant "C" is assumed, although it is possible that in some various stages, different values of C may be required for the calculation. Starting from the last stage and treating the previous stages as "black boxes," the cascade can be handled by recursively considering the two-stage case. Equation (4) and (6) can be simplified to:

$$\sqrt{ACPR_{cascade}} = \sqrt{ACPR_1} + \sqrt{ACPR_2} \qquad (7)$$



▲ **Figure 2. A WCDMA transmit chain.**

	Pin (dBm)	Pout (dBm)	ACPR (dB)	OIMD3 Pout(dB)	C (dB)
Modulator	–25	–3.7	–50.4	–43.1	7.3
Upconverter	–7	–9.9	–47.0	–38.5	8.5
Drive	–12	9.7	–49.4	–41	7.6
Power Amplifier	2	27	–37.6	–29	8.1

▲ **Table 1. The relationship between ACPR and output intermodulation ratio.**

	Pin (dBm)	Pout (dBm)	ACPR (dB)
Upconverter	–7	–9.9	–47
Driver	–11.5	10.5	–47
Cascaded with a 1.6 dB pad	–7	10.5	–40.6

▲ **Table 2. Cascade upconverter and driver.**

	Pin (dBm)	Pout (dBm)	ACPR (dB)
Upconverter	–7	–9.9	–47
Driver	–12	9.7	–49.4
Cascaded with a 2.1 dB pad	–7	9.7	–42.0

▲ **Table 3. Cascade upconverter and driver continued.**

	Pin (dBm)	Pout (dBm)	ACPR (dB)
PA	2	27	–37.6
Cascaded with a 7.7 dB pad	–7	27	–35.2

▲ **Table 4. Cascade upconverter, driver and power amplifier.**

	Pin (dBm)	Pout (dBm)	ACPR (dB)
Driver	–10	11.2	–37.5
PA	2	27	–37.6
Cascaded with a 9.2 pad	–10	27	–34.2

▲ **Table 5. Cascade driver and PA in equal ACPR.**

$$ACPR_{cascade} = ACPR_1 + ACPR_2 \quad (8)$$

When each stage has the same ACPR, Equation (7) for the correlated case obeys the 6 dB addition rule for voltage, whereas Equation (8) for the uncorrelated case obeys the 3 dB addition rule for power.

Measurement results

Laboratory measurements were performed to test the previous assumptions and conclusions discussed in this article using a WCDMA transmitter. As shown in Figure 2, the circuits consist of a modulator, an upconverter, a driver and a power amplifier. The results are as follows.

Values for the constant *C* for each component were calculated by measuring the P_{out}, ACPR and OIMD3 (see Table 1). Note that the measured values of “C” for the various stages are all similar, which indicates the assumptions made previously are reasonable.

The second step is to verify the 6 dB/3 dB rule. Both the upconverter and driver are set to ACPR –47 dB to observe the cascaded result. The measured data is given in Table 2. By changing to 2.1 dB, we obtain the results shown in Table 3. When the power amplifier (PA) is added, results, as shown in Table 4, were obtained. The two-stage cascade with driver and PA contains the measurement data shown in Table 5.

The data in Table 5 shows that the cascade summation is approximately 3 dB for driver and PA cascade and 6 dB for upconverter and driver cascade. This shows that the appropriate summation rule for cascaded ACPR can be either correlated or uncorrelated, depending on which transmitter stages are involved.

Stage ACPR specification allocation

One way to allocate an ACPR specification to each stage is by using the “6 dB down rule.” This method assumes that the stages later in the transmitter chain will operate at higher drive levels and will therefore generate more ACPR. For example, there are four stages in the WCDMA transmitter chain. Stage 1 through Stage 4 represent the modulator, upconverter, driver and PA, respectively.

When the system ACPR specification of WCDMA is –36 dBc (3 dB margin), if PA ACPR is set to –42 dBc, the total allowable cascade ACPR of the previous stages is –42 dBc. Next, the allocated driver ACPR is –48 dBc. Therefore, the total allowable cascade ACPR of previous stages is –48 dBc. Further allocating up-converter ACPR to –54 dBc, the ACPR of the modulator at the first stage could be –54 dBc.

The backward gradient allocation is usually practical because having more nonlinearity in the high power stages will have higher power-added efficiency and save current. However, this is not always a necessity when a certain stage has difficulty achieving the ACPR by the "6 dB down rule." Equations (4) and (6) show that the addition does not depend on the sequential order of the devices. Each stage contributed equally to the total cascaded ACPR.

The measured data shows that sometimes the "6 dB down rule" may be excessive and the "3 dB down rule" should be applied instead. Due to these uncertainties, the correlation varies between these two extremes. To select one over the other rule requires knowledge derived from measurement. The measurement shows that the later stages obeyed the 3 dB addition; the early stages obeyed 6 dB addition. One possible explanation is that large-signal and higher order nonlinearity make intermodulation products uncorrelated.

Cascade ACPR with channel filter

The equal weight situation can be changed if a filter with channel bandwidth is present in the chain. In a superheterodyne transmitter, an intermediate frequency (IF) filter can usually be added after the modulator. Using the uncorrelated addition with a simpler equation as an example, the cascade ACPR for the previous WCDMA transmitter becomes:

$$ACPR_{cascade} = \alpha ACPR_1 + \beta_2 ACPR_2 \\ \beta_3 ACPR_3 + \beta_4 ACPR_n \tag{9}$$

where α is the attenuation of the filter at the adjacent channel in a decimal number. If the IF surface acoustic wave (SAW) filter has 20 dB rejection at the adjacent channel, α = 0.01, the ACPR requirement will be dramatically reduced for the modulator on a 1 dB for 1 dB basis. In addition to reducing the ACPR requirements for the stages preceding it, the filter will allow the requirements for subsequent stages to be somewhat relaxed and still yield a given cascaded result. As expected, the addition of the filter largely affects the cascaded ACPR measured at the stage immediately following. It has a diminishing effect on the overall ACPR measured at the outputs of further subsequent stages.

Possible analogy for ALT

The cascade ALT can be approximated in a similar way as cascade ACPR, assuming that:

$$[ALT] = [OIMD5] - [P_{out}] - C' \tag{10}$$

The cascade ALT approximation analogy is worth investigating in future articles.

Equivalency of IP3 and ACPR

The use of the cascade ACPR formulae for the transmitter system analysis has been shown. In the system cascade, the ACPR and IP3 should be considered equivalent.

Since the output third-order intercept point OIP3 and output fifth order intercept point OIP5 are related to the output intermodulation ratio as:

$$[OIP3] = [P_{out}] - \left(\frac{1}{2}\right)\left([OIMD3] - [P_{out}]\right) = \\ [P_{out}] - \left(\frac{1}{2}\right)\left([ACPR] + [C]\right) \tag{11}$$

and

$$[OIP5] = [P_{out}] - \left(\frac{1}{4}\right)\left([OIMD5] - [P_{out}]\right) = \\ [P_{out}] - \left(\frac{1}{4}\right)\left([ALT] + [C']\right) \tag{12}$$

once the P_{out} condition is known, the mapping between ACPR and OIP3 and the mapping between ALT and OIP5 are fixed for constant C and C´. From the measurement of either ACPR or OIP3, the other can be calculated. The cascading calculation can be performed by using either ACPR or OIP3, measured for each stage at the signal level it will experience in the actual cascade.

Conclusion

The cascaded system ACPR can be approximated by using the formula derived from the intermodulation ratio cascading method. Measurement results have validated the accuracy for practical transmitter design. Mapping between the intercept point and ACPR makes the cascade of IP3 and ACPR equivalent. The cascade uncertainty depends upon the correlation of intermodulation products. ■

Author information

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