ELEX 7860 : Wireless System Design
2024 Winter Term

RF Design - IP3

Introduction

RF equipment such as receivers and transmitters are usually designed as combinations of higher-level blocks such as amplifiers, mixers, filters, etc. rather than discrete components such as capacitors, resistors etc.

Signals in these RF circuits are characterized in the frequency domain by specifying their frequencies and powers rather than as voltages and currents as might be done at lower frequencies.

In this lecture we will study this type of block-level RF design.

Each RF signal processing block is designed using a standard input and output impedance, typically 50 ohms. This allows blocks to be connected in series (cascade) without requiring the design of custom impedance matching circuits between blocks.

The signals at the points between blocks are specified in terms of their frequencies and powers (typically in dBm).

Typical RF Components

Amplifiers amplify the input RF signal. Amplifiers can be tailored for different purposes. Different amplifiers might be designed for a low noise figure, a high output power, low distortion, wide bandwidth, etc. Amplifiers can also be designed to have variable gain (a Variable Gain Amplifier or VGA).

Attenuators attenuate the input signal. They can also be used for impedance matching and to provide isolation between the input and output. Attenuators can be fixed, switchable or (rarely) variable.

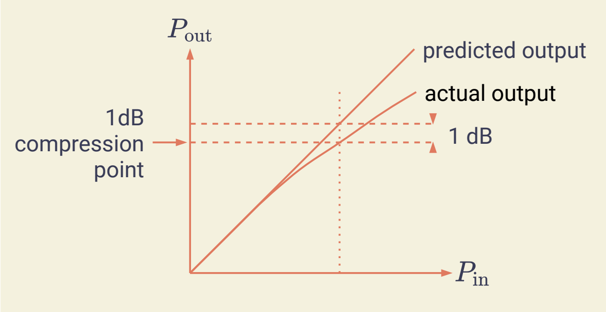
Frequency mixers (also simply called mixers) multiply two signals. The result has components at frequencies equal to the sum and difference of the input frequencies. There are both passive mixers, of which the double-balanced mixer (DBM) is probably the most popular, and active mixers.

Filters attenuate specific frequency ranges. They can be high-pass, low-pass, band-pass, etc. There are many technologies that can be used to build filters including lumped-element (LC), various types of resonant structures, and surface acoustic wave (SAW).

Gain and Non-Linear Distortion

The ratio of output power to input power is the gain. This is typically a function of the frequency and is specified in dB.

Active devices have limits to how much power they can output. Because of this the gain of an active device such as an amplifier is usually a function of the input level. As the device approaches its maximum output power the gain of the device will drop. The output level at which the output power drops by 1 dB from the theoretical output is called the *1 dB compression point*.



Any non-linear amplification of the signal causes distortion which results in additional frequency components being generated.

We can expand the output vs input characteristic of the amplifier using a Taylor series:

$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots$$

where v_o and v_i are the output and input signals respectively.

The first- and third-order terms are the most interesting because they result in frequency components at or near the carrier frequency as we will see shortly. Assuming a sinusoidal input of $A\cos(\omega_1 t)$, expanding these two terms and assuming $a_1 \gg a_3$ it can be shown that the output is:

$$v_o = a_1 A \cos(\omega_1 t) + \frac{a_3 A^3}{4} \cos(3\omega_1 t)$$

Converting to dB and plotting the levels of these two components shows that the level in dB of the fundamental increases linearly with the input amplitude, A, but the third harmonic increases three times faster:

$$v_o(\text{dB}) = 20\log(A) + 20\log(a_1) +$$

$$60\log(A) + 20\log(a_3/4)$$

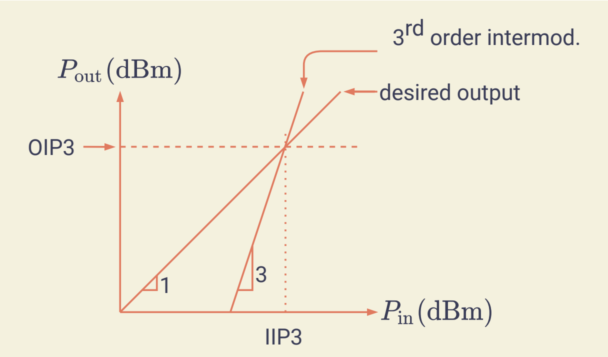
The same relationship holds for other third-order products.

Intermodulation

If the input consists of two sinusoids at frequencies of ω_1 and ω_2 the output will contain not just the harmonics of these frequencies but also "intermodulation" products at frequencies $n\omega_1 \pm m\omega_2$ where n and m are positive integers.

The third-order "intermod" frequency components are those where $n + m = 3$. The components at $2\omega_1 - \omega 2$ and $2\omega_2 - \omega_1$ are of particular interest because these components appear spaced from the original components by the difference in frequency between the two components. This is important because if the two components correspond to components that fall within an assigned channel, as would be the case with most transmitted signals, the third-order products will fall in an adjacent channel – something that's undesirable because it would cause interference to another user.

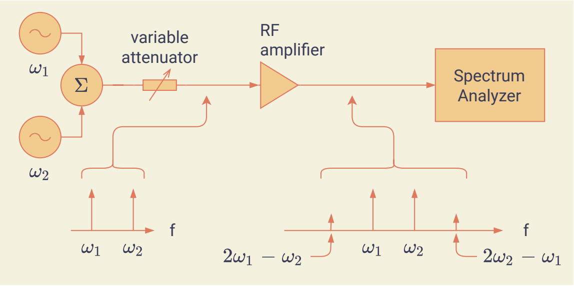
Exercise 1: If the two input frequencies are 150 and 155 MHZ, what are the frequencies of the third-order products? If these two frequencies represent the lower and upper frequencies of a channel, what is the channel bandwidth? Where would the third-order products fall relative to the adjacent channel?



The power at which the third-order component would have the same power as the fundamental is called the third order intercept point (IP3). IP3 can be specified as either the input power (IIP3, useful when input overloading is a consideration as in the case of an low-noise amplifier) or output power (OIP3, useful when the output power is the main specification of interest). The two are related by the theoretical gain of the amplifier.

Measuring IP3

The figure below shows how IP3 can be measured in the lab by using an input signal consisting of two sinusoids and a spectrum analyzer to look at how the output levels of the fundamental and third-order products vary as the input level is changed:



The input and output levels of the fundamental and a third-order product are measured in dBm as the input signal level is raised while the output level is within the linear range. Two straight lines are extrapolated and the intersection of two is computed as in the diagram above. This is the measured IP3 of the amplifier.

Using IP3

The IP3 of an amplifier is useful for calculating the amplifier output power as a function of the level of the third-order products. Typically the level of the third-order products represent adjacent-channel power that needs to be kept to a certain level relative to the power of the fundamental component. Since the third-order products decrease by 3dB for every 1dB reduction in fundamental power, it is easy to evaluate how much the fundamental (desired signal power) needs to be reduced below the OIP3 point.

Exercise 2: An amplifier has an OIP3 of 30dBm. If it is required that the adjacent channel power be 30dB below the in-channel power, what is the maximum output power we should try to get from this amplifier?

Cascade IP3

When multiple amplifiers are connected in series (cascade) the signal level at the input to the second amplifier is higher than the level at the input to the first stage. We would thus expect that the IP3 of the cascade would be determined primarily by the IP3 of the final amplifier.

It is possible to show that the input IP3 (in linear units) of a cascade of amplifiers with gains $G_1, G_2, \ldots$ and input IP3's $I_1, I_2 \ldots$ is:

$$\frac{1}{IIP3} = \frac{1}{I_1} + \frac{G_1}{I_2} + \frac{G_1 G_2}{I_3} + \ldots$$

When the gains are significant, the IIP3 of the last stage predominates.