Adjacent Channel Effects of Nonlinear Circuits

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Abstract

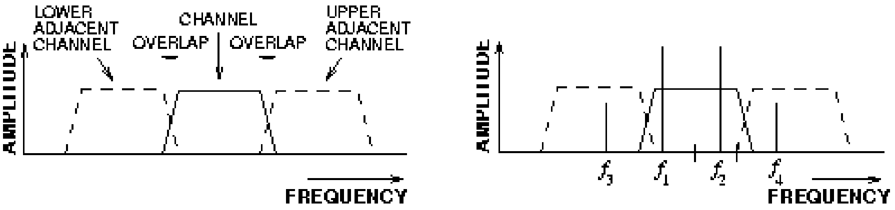
Spectral regrowth in power amplification of digitally modulated signals can be partly explained by considering intermodulation of discrete signals. A full description however requires statistical modelling. An accurate modelling approach for predicting spectral regrowth and the origins of asymmetric adjacent channel distortion in digital radio are presented.

I. INTRODUCTION

One of the most competitive areas of RF and microwave circuit design is the design of highly efficient power amplifiers for cellular radio handsets. The major design constraint is achieving efficiency while achieving maximum specified levels of distortion in the channels adjacent to the channel being used by a particular handset. In some systems, such as analogue systems and GSM, frequency planning is required to cope with interference so that the set of available channels are distributed among the cells in a cluster and the cells within a cluster and the clusters themselves are arranged so that the same frequency channels are not used in neighbouring cells. Thus there are always one or two intervening cells between cells that reuse the same channels. In CDMA systems the concept of clusters is not used and channels are reused in adjoining cells. That is, channels adjacent to a main channel are used for communication in the same cell. Distortion introduced in adjacent channels is therefore more significant than with other systems (with the notable exception of CDMA). In all cellular systems it is necessary for the system design to impose maximum levels on the amount of distortion that can be introduced in adjacent cells. Since it is not possible to design for absolute distortion levels, relative levels of power in the adjacent channel to power radiated in the main channel is imposed. The most commonly used measure of this distortion is called Adjacent Channel Power Ratio, ACPR—$\mathrm{ACPR}_{\mathrm{LOWER}}$ and $\mathrm{ACPR}_{\mathrm{UPPER}}$ referring to the ratio of the power in the main channel to the power in the lower and the upper adjacent channel respectively. It is the purpose of this paper to present a tutorial and review of our understanding of the mechanisms that produce this distortion. While a digitally radio system can be modelled in a variety of ways [1], simple behavioural modelling is required to develop fundamental understanding [2], [3].

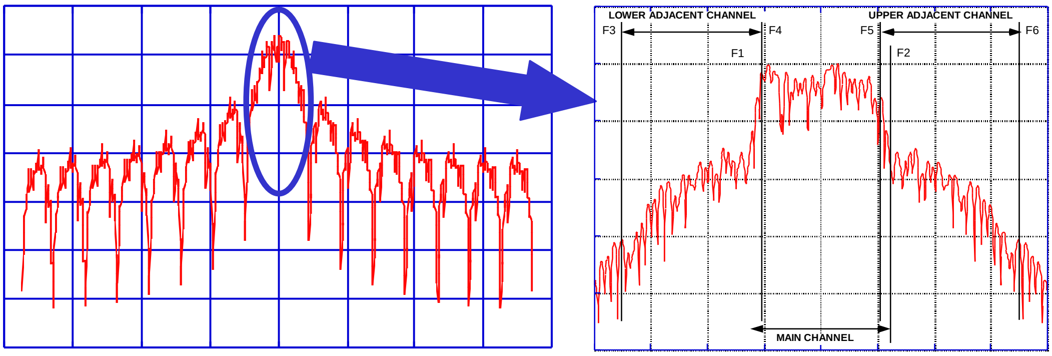
II. Distortion in RF Cellular Communication Systems

Channels in most cellular systems are arranged to be overlapping so that some power intended for a main channel inherently appears in the adjacent channels so that there is a minimum level of ACPR, see Figure 1(a). The overlap is a comprise between the finite roll-offs of filters and the need to maximize spectral efficiency. One of the key attributes of digitally modulated signals is that with the modulation formats used, the spectrum of the modulated signal is almost flat in the centre with reasonably sharp skirts. Never-the-less power is still produced in the neighbouring channel regions. Figure 2(a) is a broad spectrum view of a p/4QPSK modulated signal. An expanded view of this spectrum showing the main channel and the lower and upper adjacent channels is shown in Figure 2(b). The spectrum shown in Figure 2(b) was calculated for a 512 symbol sequence. It is common to see a much smoother version of this spectrum but this is only obtained if a very long sequence is considered. For actual packet lengths (e.g. 147 in GSM) the spectrum is not smooth and in fact changes shapes for different packets with different symbol sequences.



(a) (b)

Figure 1: Spectrum of a cellular radio system showing the main channel and adjacent channels: (a) overlapping main and adjacent channels and stylised spectrum shape of a digitally modulated signal; and (b) superimposed two-tone signal (with tones at f_1 and f_2).



(a) (b)

Figure 2: A digitally modulated signal: (a) Broad spectrum view of modulation; and (b) narrow spectrum view encompassing the main channel and the lower and upper adjacent channels.

The transmit subsystem responsible for the spectral shape can be represented by its baseband equivalent as shown in Figure 3. What this model is telling us is that the transmit communication portion of a handset can be represented by parts that are linear followed by a nonlinear amplifier. This amplifier can be behaviourally modelled by a complex power series [3]. That is a power series with complex coefficients and an input that consists of the two modulating bit streams $x(t)$ and $y(t)$. The stage is now set to begin our description of the origins of intermodulation and spectral regrowth.

What we really want to determine is the level of spectral regrowth and an understanding of how to design a circuit that will affect these levels. For reasons that will become apparent later, considering a digitally modulated signal first is not the best way to develop insight. It is much more convenient to first discuss the origins of intermodulation distortion with discrete tones as in Figure 1(b).

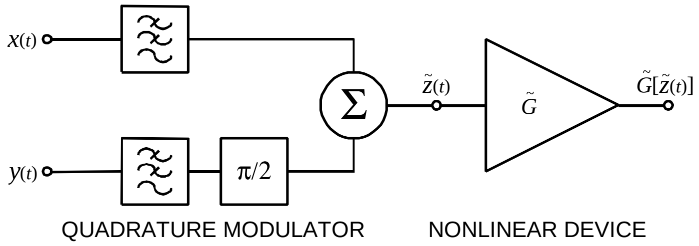


Figure 3: Baseband equivalent representation of a quadrature modulator.

III. INTERMODULATION DISTORTION

The process of signal modification through a nonlinear amplifier can be viewed as one of mapping an input signal to an output signal. When the input signal can be represented as a sum of sinusoids— a reasonable representation for a signal that is analogue modulated (e.g. FM modulation in the AMPS system)— the process becomes one of mapping a set of input phasors to a set of output phasors. The nonlinear performance of an amplifier with this type of signal is quantified using a two tone test. This test results in the spectra shown in Figure 4 at the output of the nonlinear amplifier. The input consists of just two tones, f_1 and f_2, and the nonlinear process appears as a mapping of the two tone spectra to the multi-tone spectra of Figure 4. The nonlinear process produces all possible sum and difference frequencies of the integer powers of the input tones. The troublesome tones are the additional tones occurring close to the original tones as these cannot be removed by filtering. The other additional tones (in frequency groups f_B, f_C and f_D) can be removed from the output signal by filtering however they will appear internal to the amplifier and so are involved in the nonlinear mixing process. One way of viewing what is happening is to consider the nonlinear process in two parts. The two-tone signal is applied to the first part which results in the spectra of Figure 4. This spectra is then applied to the second nonlinear part which produces much the same spectra. It is necessary to truncate high order mixing from the process. Many of the effects encountered in nonlinear distortion can be described by considering the processes involved in producing the tone f_4. This tone is commonly called the lower third order intermodulation component IM_3. This terminology is not completely accurate as other intermodulation orders are involved. The ratio of the power in the two main tones f_1 and f_2 to the power of IM_3 is called the third order intermodulation ratio, IMR_3. The level of IM_3 is the vectorial sum of a number of discrete intermodulation processes of different order. An asymmetry in the lower IM_3 and upper IM_3 is commonly observed [4]. Removing the asymmetry in the intermod response requires that attention be given to the baseband impedance presented to the amplifier. The insight provided by this analysis raises the possibility that ultra linear amplifiers can be developed with the terminations at the different frequency bands adjusted so that the vectorial sum is minimized.

IV. DIGITAL SIGNAL DISTORTION

Interpretation of the digital process with a digitally modulated signal is complicated by the input signal being best represented by a waveform and the output signal interpreted in the frequency domain. Until recently it has not been possible to merge these domains in an analysis. Building on concepts extending back into the sixties, the input waveform signal can be represented in the statistical domain, e.g. using the autocorrelation of the signal. It is a simple matter to obtain the autocorrelation function of the input waveform. Then the nonlinear process acting on the statistically defined signal can be viewed as a mapping taking an input correlation function and mapping this onto an output correlation function. It is then a simple matter to arrive at the output spectrum from the output autocorrelation function. A reasonably simple relationship maps the input autocorrelation function onto the output autocorrelation function [3]. The relationship is not given here but it has the form of sums of higher order estimated values of the input signal each multiplied by the corresponding complex power series coefficient. The high order estimated values of cross-correlations of the signal are derived from the autocorrelation function of the input signal. Thus the autocorrelation function of the output signal depends on the power series coefficients and the autocorrelation function of the input signal. This model provides an excellent prediction of ACPR as shown in Figure 5(a) for a narrowband CDMA signal for various orders of the power series. With a 13 th order power series model the measured and predicted ACPR are virtually coincident (not shown in the figure).

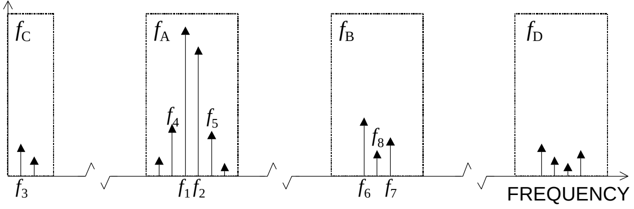
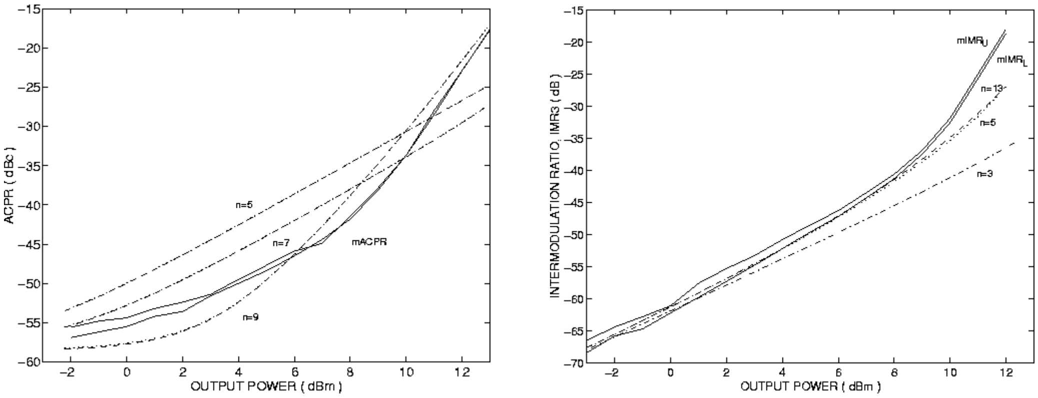


Figure 4: Spectrum in a nonlinear system with two tone input signal at frequencies f_1 and f_2.



(a) (b)

Figure 5: Modelled and measured distortion: (a) ACPR for a digitally modulated signal (OQPSK); and (b) IMR3 for a two tone signal.

V. CONCLUSIONS

A method for the estimation of spectral regrowth of digitally modulated signals passed through a nonlinear device modeled by a complex power series has been presented. The origins of spectral regrowth were discussed here. One of the important results was to show that intermodulation distortion of a discrete tone signal and spectral regrowth of a digitally modulated signal are directly related but not in a simple way that two-tone intermodulation results can be used to guide design. Design methodologies such as the envelope-termination method [4] coupled with the design insight presented here have successfully been used to develop low distortion high power digital radio transmitters.

VI. REFERENCES

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