Simulation Method to Extract Characteristics for Digital Wireless Communication Systems

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Abstract

In all wireless standards involving digital modulation, new fundamental characteristics have to be extracted for quantifying the linearity/distortion in RF designs. This paper describes a simulation technique, Modulated Steady State, and its use to extract these specifications. An example of its application to a typical RF transmitter with a π/4-DQPSK modulator is presented.

1. Introduction

Digital modulation is a fundamental function in wireless communication systems because, instead of analog modulation, it offers increased channel capacity and enhances the transmission quality. Since, a digitally modulated signal can only be represented as a power spectrum density [1], new characterization and representation of problem have to be quantified with respect to the RF specifications. For instance, one of the most important aspect of modulation technique that is of great concern in RF design is the power efficiency attributing to the type of power amplifier used in the transmitter. The nonlinearity of PAs can be characterized by a two-tone method (third order inter-modulation) but it becomes inefficient in presence of digital modulation signals. With a variable envelope input waveform, the spectrum tends to grow out the bandwidth of the signal channel through a nonlinear system (also called the spectral regrowth). To quantify this aspect, in the next section, it will be shown some main characteristics needed in digital modulation applications. Section 3 will describe the used simulation technique and Section 4 is an application of the methodology to a typical RF transmitter with a π/4-DQPSK modulator.

2. Main characteristics for digital modulation applications.

• In digital modulation, the spectral regrowth is an important aspect figuring out the corruption by the signal channel to the adjacent channels. This phenomenon can be quantified by comparing the power in the adjacent channel to the power in the main channel (Fig. 1): Adjacent-Channel Power Ratio (ACPR) [1] is now a popular figure-of-merit for characterizing the efficiency amplification in digital wireless communication systems.

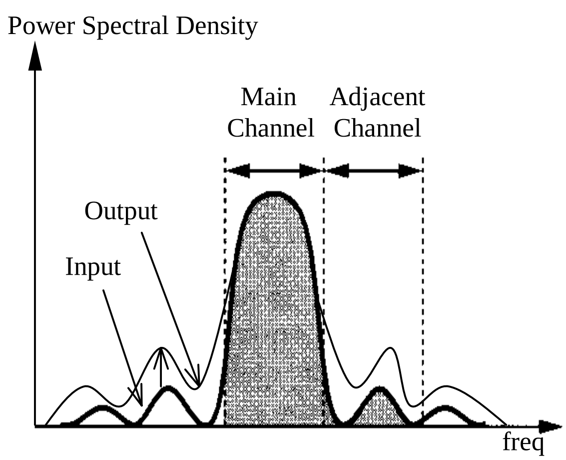

Figure 1 – Main and adjacent channel power.

We define ACPR characteristic as:

$$ACPR = \frac{P_{Adjacent-Channel}}{P_{MainChannel}} \quad (1)$$

The bandwidth for the adjacent and main channels may be defined by the user. ACPR is usually expressed in dBc.

• Digital wireless communication systems use multiplexing channels. These later have some statistic properties close to the white gaussian noise characterized by a bandwidth limited power spectral density (PSD). Since, by using this kind of PSD, it is introduced the Noise Power Ratio (NPR) characteristic to measure the nonlinear behavior of these systems. The principle is to set to zero the center input channel ("notched off"). The generated intermodulation products due to the nonlinearity of the system will fill in the "hole". NPR is the ratio of the filled channel power and the notched channel one.

$$NPR = \frac{P_{Filled\,Channel}}{P_{Notched\,Channel}} \quad (2)$$

• Digitally modulated signals are usually represented in a constellation diagram (I/Q format). At each symbol clock-transition, the signal's magnitude and phase of the carrier occupy one particular valid location on the I/Q format corresponding to a specific data symbol. Error Vector Magnitude (EVM) is the residual difference between the ideal "reference" signal and the actually measured one in term of magnitude and phase. It characterizes the distorted constellation and is directly deduced from the constellation diagram. It is also crucial to determine the crest factor or peak-to-average ratio of the signal before amplification. We define it as the ratio of the instantaneous peak value, i.e. maximum magnitude, of the signal to its time-averaged value.

3. Modulated Steady State (MSS)

Modern Harmonic Balance [2] is an efficient and fast Steady State frequency-domain analysis method. However, in presence of digitally modulated sources, Harmonic Balance method is not well adapted because it can only handle (quasi-) periodic signals.

A mixed time-frequency method has been developped [3-4] to support such signals, where the low-frequency part is computed by a transient algorithm and the high-frequency part is computed by a Harmonic Balance technique. Modulated Steady-State analysis is based on this method.

Using a modified nodal formulation, let us consider the Kirchhoff Current Law at the N circuit nodes in time domain. It leads to a system of nonlinear ordinary differential algebraic equations of dimension N:

$$i(v(t)) + \frac{dq(v(t))}{dt} + i^s(t) = 0 \quad (3)$$

where *i(.)* is the vector of sums of currents entering each node and branch voltages and *q(.)* the vector of charges and fluxes, both depending on *v(t)*. Let us assume that the circuit is stimulated by digitally modulated sources $i^s(t)$. Then we represent the vector of node voltages *v(t)* using a finite time-varying Fourier envelope formulation:

$$v(t) = \sum_{k=-K}^{+K} V_k(t) e^{j\omega_k t} \quad (4)$$

with ω_k is the pulsation corresponding to the k^{th} harmonic and $V_k(t)$ are the unknown time-varying harmonic Fourier components which are solutions of:

$$I_k(V(t)) + j\omega_k Q_k(V(t)) + \frac{dQ_k(V(t))}{dt} + I_k^s(t) = 0 \quad (5)$$

With respect to the Harmonic Balance equation, the additional third term represents the variation of charge at the harmonic *k* caused by a time-varying change in the voltage. MSS applies a time-domain technique on top of the frequency-domain harmonic balance solution during simulation. The derivative term can be computed using any order of integration (Backward-Euler, Trapezoidal, Gear). The time-domain is handled by the analog simulator *Eldo* in term of variable time-step control (LTE, accuracy options) such as in a regular transient analysis. At each time point, a Steady-State analysis is performed in frequency-domain. MSS has been implemented in the RF simulator *Eldo RF* [5].

Additionnally, MSS simulation technique internally contains a new efficient algorithm. The signals at analog nodes are generally low-frequency ones and can be computed by a regular transient analysis. The modulated signals at "RF" nodes are generally composed by a slow modulation called envelope and a high frequency carrier. These signals are computed by MSS. The idea is to deal with analog and RF signals in the same analysis. The algorithm we used for our tests is based on a modulated steady state algorithm (MSS) with an improved Harmonic Balance kernel using Frequency Domain Latency (FDL) [6].

Indeed, if we allow a variable number of harmonics for each node, i.e for the node *i*, we write:

$$v_i(t) = \sum_{k=-K_i}^{+K_i} V_{i,k}(t) e^{j\omega_k t} \quad (6)$$

Note that if $K_i = 0$ in (6) then

$$v_i(t) = V_{i,0}(t) \quad (7)$$

which is a purely transient representation. Consequently, this coefficient is only computed by the upper transient loop of the MSS algorithm without any cost of Harmonic Balance. Then for the analog nodes, K_i can be set to 0, and for RF nodes, K_i must be chosen so that the truncation error is sufficiently small. The entire description of this technique is beyond the scope of this study and will be detailed in further publications.

4. Illustration of simulation capabilities

This new methodology is a consistent improvement in comparison with a regular RF analysis where the modulated sources are only considered as RF ones. Now we can analyse modulators even in their internal structure, from the digital NRZ data stream to the analog and RF signals. The simulation/verification of the digital part is a crucial issue.

In typical transmitters and receivers, many operations take place in the digital domain: voice encoding, voice compression, error correction, interleaving, symbol encoding for transmission and respectively demodulation, equalizing, de-interleaving, decoding, voice decompression for reception. All these tasks are commonly called Digital Signal Processing (DSP). The simulation/verification of DSP cannot be handled easily in an analog way. Digital simulators perform specific event-driven algorithms to accomplish this work.

Consequently, we have to imagine the coupling of our analog-RF simulator with an event-driven DSP engine. The interface between the two simulators typically consists of analog-to-digital and digital-to-analog converters. Then we obtain a universal tool, where each part, RF, analog, digital is simulated with its specific optimal algorithms in a unique analysis.

We currently perform the DSP part independantly and we consider its digital outputs as analog entries of the MSS engine.

The application focuses on the basic implementation of a transmitter with Square Root Raised Cosine (SRRC) $\pi/4$-DQPSK modulation, described in Fig. 2. This modulation format is typical of current NADC (IS-54/136) systems [7]. The pulses of the NRZ data stream of unity amplitude are modulated by a $\pi/4$-DQPSK modulator, the I (Inphase) and Q (Quadrature) components of the modulation being shaped by a Square Root Raised Cosine (SRRC) filter with a roll-off factor of β=0.35 (NADC standard). Then the resulting signal is amplified by a PA before transmission.

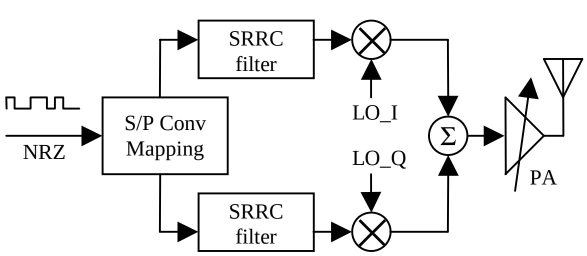

Fig. 2 – Basic implementation of a transmitter with SRRC $\pi/4$-DQPSK modulation.

The spectrum of the signal at the input and output of the PA is obtained by a simple FFT on the complex time-varying spectrum obtained thanks to MSS. We observe the spectral regrowth due to nonlinear amplification. It is characterized by out-of-channel power which may corrupt adjacent channels (see Fig. 3).

The simulation is executed with a circuit description at transistor-level and the ACPR value is extracted by the simulator after the simulation. For a carrier frequency of 850 MHz and a carrier spacing of 30 kHz, the signal exhibits an upper ACPR of –28.7 dBc and a lower ACPR of –30.3 dBc.

Trajectory diagram is displayed by plotting the Q channel trajectory versus the I channel trajectory (see Fig. 4).

The constellation diagram is obtained by sampling the trajectory diagram at the symbol rate (see Fig. 5). EVM can directly be extracted from the constellation diagram. We found an EVM of 6.2 % and an average phase error of 2.1 degrees.

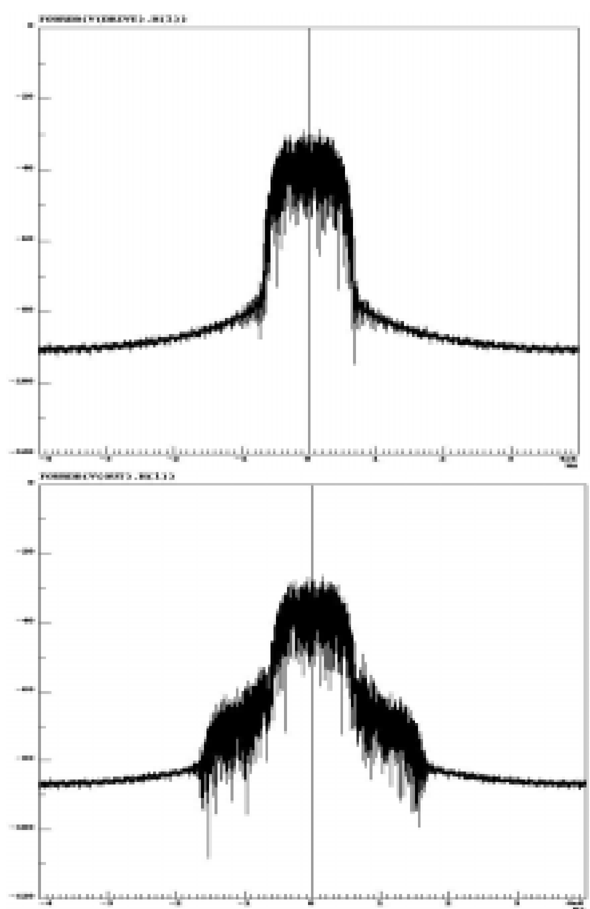

Fig. 3 – Input (top) and output (bottom) spectrum with SRRC $\pi/4$-DQPSK modulation.

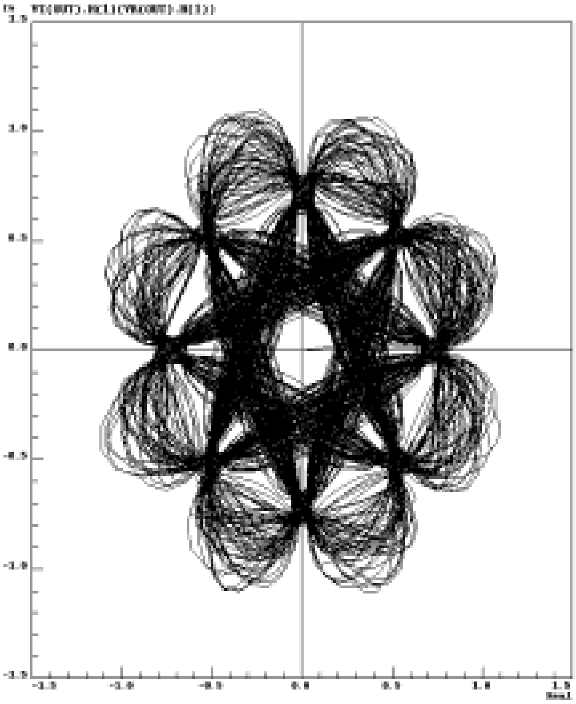

Fig. 4 – Output trajectory diagram with SRRC π/4-DQPSK modulation.

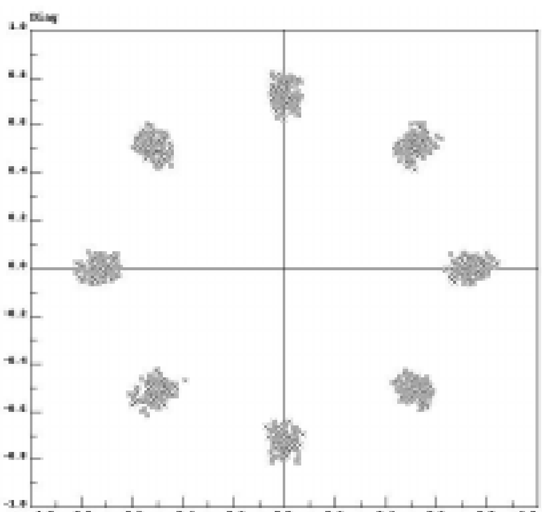

Fig. 5 – Output Constellation diagram with SRRC π/4-DQPSK modulation.

5. Conclusion

Traditional steady-state methods such as Harmonic Balance or shooting are not efficient to handle digitally modulated signals arising in all modern wireless communications systems. We have presented an algorithm called Modulated Steady-State. This analysis is particularly efficient to simulate/verify modern communication systems and to extract their required characteristics. This is implemented in an Analog/RF simulator and is illustrated on a typical RF transmitter with all the main characteristics such as ACPR, NPR, EVM.

6. Bibliography

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