2-1 (Invited)

RF IC Simulation: state-of-the-art and future trends

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Introduction

In the past decade there has been an exponential growth in the consumer market for wireless products. Products like pagers, cordless and cellular phones are now common products for consumers all over the world. But also computers are no longer connected to other computers and their peripherals by copper wires only: wireless computer networks are used more and more. Not yet very common but growing steadily are the wireless home systems, connecting all kinds of equipment present in peoples homes. Furthermore there are promising markets in the automotive area in vehicular navigation and inter-vehicular communication.

The change from mainly professional wireless applications (military, private mobile radio, etc.) to a consumer market has severe implications for the total design process. Where in the past there was time to build and measure several prototypes, nowadays the demands on time-to-market, time-to-quality, price, production volume, etc. are so severe that designers have to resort to simulation. In a marketing window of only a few months there clearly is no time for several iterations of these systems-on-silicon.

Although the RF part of these systems constitutes only a minor part of the total design area, it presents a major challenge in the total design cycle. This challenge is caused by the analogue/RF nature of the design but also by the lack of appropriate tools, models and design flows. Because the demand for RF simulation tools on this scale is relatively new, the developments of tools (the underlying principles and the commercial implementation there of) are lagging behind the designers' needs. It is clear that we are only in the start-up phase of RF tooling and RF design flow development. Nevertheless, recently a lot of progress has been made in the research of mathematical principles for RF simulation. A number of these new ideas are already available in commercial software.

This paper deals with an overview of principles of RF simulation, zooms in on the current limitations of the methods and discusses some anticipated future directions.

RF circuits

RF circuit and signal characteristics

An RF circuit forms the link between some baseband information signal and an antenna. A transmitter modulates the baseband signal on a high frequency carrier (sinusoid) and the task of the receiver is to retrieve the baseband signal from the modulated carrier. Thus, as compared to baseband circuits, RF circuits are special in the sense that they process modulated carriers. In the frequency domain a modulated carrier is a narrow band signal where the absolute bandwidth is related to the frequency of the carrier signal and the relative bandwidth is related to the modulating baseband signal. Practically, the ratio of the two frequencies is in the order of 100 or 1000.

Another major difference is that in RF systems, noise is a major issue. Noise consists of the (usually) small unwanted signals in a system. One can think of several forms of device noise (thermal noise, shot noise, flicker noise) but also of interferers like neighbouring channels, mirror frequencies, etc. All noise sources are of major importance because they directly translate to bit-error-rates of the transmitted data. Therefore it is imperative that RF designers can predict the overall noise quickly and accurately.

When dealing with narrow band signals in a noisy environment two mechanisms are of major importance. Firstly, if a narrow band signal is passed through a non-linearity, the spectrum will be repeated about integer multiples of the carrier frequency resulting in a very wide but 'sparse' spectrum. Secondly, the signal will interact with other signals in the circuit leading to wanted and unwanted frequency shifts. Although both mechanisms are always present and even interact, the first mechanism is less important for small signal levels (e.g. noise). Both mechanisms are illustrated separately in Figure 1 below where the input signal might represent a real input to your system but also an internal noise source. It can be seen that overall this will result in signals with a very wide but sparse spectrum.

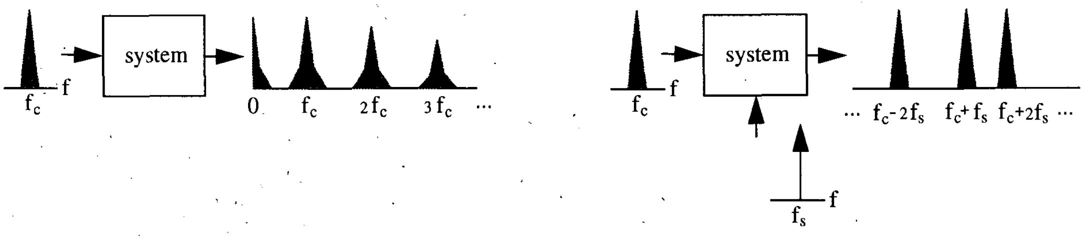

Figure 1 Non-linear behaviour and frequency shifts

RF building blocks

RF systems are typically built from a limited number of different building blocks: oscillators, mixers, amplifiers/filters, dividers and power amplifiers. When building or discussing special RF circuit simulation functionality it is important to first determine the characteristics of each building block and the information which should be obtained during simulation:

◆ Oscillators are autonomous circuits which serve as a frequency reference signal often of very high accuracy. Therefore the frequency itself must be determined accurately but it is also important to be able to determine the frequency behaviour over time i.e. the phase noise. Physically the phase noise is caused by the device noise of the oscillator's components.

◆ Mixers perform a frequency shift on the input spectrum. Because of unwanted non-linearities the input signal will not only be shifted but also distorted. Furthermore, the mixer will add noise to the signal, again generated by the devices in the circuit.

◆ Amplifiers and filters also suffer from unwanted non-linearities and add noise to the signal.

◆ Dividers are used to modify a frequency reference signal for example coming from an oscillator. They are strongly non-linear and they add phase noise to the signal.

◆ Power amplifiers are much like small signal amplifiers. However, depending on the modulation type and efficiency requirements they may be strongly non-linear. Assessing the non-linearity, especially in the frequency domain is important.

Simulating RF circuits

Simulation requirements

As mentioned earlier, noise is of major importance in RF circuit design. Depending on the required accuracy and application area the noise can be seen as a small, independent signal in the circuit. Much more often, however, the small noise signals interact with the large signals in the circuit resulting in frequency shifts of the noise spectra (noise folding). In a few cases the noise can not even be considered as a small signal but interacts with the other (noise) signals in a non-linear manner. The RF designer must be able to simulate all these different views on noise but the second one is considered the most important.

Non-linearity (harmonic distortion and intermodulation distortion) is mainly a measure for the behaviour of a circuit under unwanted strong disturbances which enter the system.

RF designers must be able to extract this information by simulating a design with reasonable turn-around times. This has to do with the actual computing time required for a simulation job but also addresses the robustness of the software. Equally important, however, is that the results are accurate and hence reliable.

Simulation methods

From the above it is clear that conventional SPICE-like simulators are not sufficient: transient simulation of RF circuits suffers from excessive CPU times because they have to deal with the absolute bandwidth of the signals and will therefore only be used when no alternatives are available (e.g. full non-linear noise simulation including time domain transient noise sources [8]). AC analysis can easily deal with the high bandwidths but does neither take into account non-linearities nor frequency shifts.

The newly developed RF simulation methods all somehow exploit the 'sparsity' of the signal spectra. The basic method is that of determining the periodic steady state (PSS) solution of a circuit. Conceptually this can be seen as a generalisation of the well-known DC operating point: for baseband circuits the spectral content around 0 Hz (the DC point) is important. For RF circuits the (narrow) spectral content around specific frequencies (the PSS solution) is of interest. This PSS solution can be obtained in the frequency domain (harmonic balance) or in the time domain (methods, like shooting, based on transient simulation methods). With baseband simulation, after determining the DC point, additional simulations like AC, noise, etc. can be done to obtain more information about the circuit. Similarly, based on the PSS solution several other simulations can be done like periodic AC, periodic noise, etc. In view of the RF circuit and signal characteristics, the PSS solution determines the non-linear behaviour of the circuit while the periodic AC, etc. deals with the frequency shift.

The main difference between the time domain and frequency domain methods to obtain the PSS solution is that the former can easily deal with strongly non-linear circuits and discontinuities and have good convergence properties while the latter deal naturally with components characterised in the frequency domain. Over the years combinations of both basic methods were developed resulting in mixed time-frequency domain approaches each with their own advantages and drawbacks (for example, circuit envelope is a time varying harmonic balance approach but can not handle elements characterised in the frequency domain). Excellent overviews of currently available methods are given in [1,2].

Open Problems

Although there has been a lot of progress in specialised RF simulation methods there still are a number of open problems surrounding this issue some of which are mentioned below.

The multi-tone problem (a circuit excited by several periodic sources with no mutual frequency relation) is not yet well-solved in commercially available software. An interesting approach [3,12] is to deal with the multi-tone problem on the basis of multi-variate signals. From this angle it seems that the shooting methods, often appreciated for their automated adaptivity of discretisation, require a major re-design in order to extend them in this direction. A time domain method based on a finite difference approach looks more promising because it is more flexible. It also opens the possibility to formulate simulation problems as partial differential equations allowing the complete arsenal of PDE solution methods to be used in RF circuit simulation.

One of the major problems still is the accurate simulation of phase noise in oscillators. The first problem is finding the PSS solution to be used as the starting point for the phase noise computation: because the exact oscillation period is not known beforehand it should be solved as a part of the total simulation problem. Furthermore, phase noise itself and how it is generated from the noise sources in the circuit is complicated and therefore it is not very clear which assumptions can be made when developing the algorithms. For example, the assumption that small noise signals always lead to small phase errors is fundamentally wrong [4]. Non-linear perturbation methods were developed to correctly simulate these large phase deviations. For the important case of 1/f (flicker) noise, research into the validation of this theory is yet to be done. For flicker noise the power spectral density (PSD) increases for lower frequencies. Because of the frequency shift mechanisms in a non-linear oscillator the 1/f spectrum is shifted towards the oscillation frequency giving rise to an important contribution in the phase noise. Especially in RF CMOS circuits this is important because MOS transistors exhibit relevant amounts of flicker noise.

Incorporating noise sources during transient simulation leads to stochastic circuit equations. For stochastic differential equations (SDEs) the theory is quite well developed [6,7,8]. Electronic circuit simulation, however, requires the analysis of stochastic differential algebraic equations (SDAEs). Here even a first order theory is lacking. This impedes the development and analysis of numerical methods for SDAEs.

In all the algorithms robustness and accuracy of the results is very important: the software should converge well and the simulation results should not change drastically when a numerical setting is slightly changed. Furthermore the simulation results should be accurate i.e. close to reality. The RF designer should be able to trust the results of the simulation software and this is an issue of implementation and the fundaments of the underlying mathematical method. For a lot of methods a solid mathematical fundament supporting these issues is still to be generated. A pragmatic approach would be to benchmark several products against each other but of course also against measurements.

As to pure software implementation aspects, we foresee a trend which is aimed at extendability of the software at the cost of performance. This is necessary to be able to more quickly modify the software according to new developments in RF simulation methods.

Clearly, the accuracy of the simulation results also depends on the accuracy of the models used. Especially in RF applications and with decreasing feature sizes the current models for active devices start to show their limitations. For static non-linear behaviour, developments are going on to be able to predict more accurately the distortion of RF circuits. Furthermore the quasi-static modelling approach is not always valid any more. This limitation has direct consequences in simulating impedance levels and maximum operating frequencies which are essential in RF design [11] but also on the noise models. The models for the PSD typically contain a bias current. Conventionally, noise simulation is performed about a DC point. Therefore the noise can be modelled as a stationary stochastic process. If the bias current becomes periodical, theoretical problems occur because as yet there are no well-established stochastic models for the non-stationary noise generation process [9]. For thermal and shot noise which both have a flat PSD (and hence a narrow auto-correlation function), it can be argued that the noise can be modelled as simply modulated by the large signal PSS solution. Because flicker noise has a non-flat PSD this reasoning does not hold and no theoretical analyses nor experimental data are available yet [9]. Models should be developed for the time as well as the frequency domain. For a first good attempt see [5]. Although progress in these areas of modelling all these effects has been made, the main challenge is to have and keep all the necessary ingredients available with on-going process technology[11].

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