Non-Linear Transient Simulation of Microwave Circuits and Systems

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Abstract

A key requirement in many future-oriented CAD environments for RF/microwave design is that they provide a general capability for truly non-linear transient analysis in the time domain. We survey the capabilities and limitations of simulation techniques that can address this kind of problem, and show a promising new approach that gives very fast and accurate results.

1. Introduction

Successful high-frequency non-linear analysis and design at the circuit level is critically dependent on developments in two core aspects, firstly, accurate but compact active device models and secondly, efficient and reliable simulation techniques [1][2]. This contribution concentrates on the second of these, particularly on the most general case of non-linear transient simulation. For many years microwave engineers have been well served by a range of simulation approaches that assume a steady-state solution, in particular Harmonic Balance (HB) and its variants [3]. Increasingly however, the demands for more complex signal formats, wider frequency ranges and more difficult operating conditions, create quite new challenges for standard simulation techniques.

We begin by briefly reviewing a number of existing techniques and then describe progress on a different approach that is based on an effective method for describing arbitrary frequency domain sub-systems or blocks in discrete time. This approach is adaptable in the sense that it can not only find an exact transient solution, but also find that solution plus a steady-state solution, or, alternatively, if the transient is of no interest it can use an artificial (and very short) 'pseudo-transient' pre-solution to proceed directly to the steady-state. Several illustrative examples are given.

2. Review of Existing Techniques

The most well known transient simulator in electronic engineering is SPICE, together with its many variants [5]. SPICE pioneered a Modified Nodal Analysis technique still widely used in modern simulation environments. A short summary of the advantages of this kind of approach (compared to HB) might be:

- starts from DC and makes no “a priori” assumptions about dynamic behaviour;
- general excitations possible;
- robust and accurate.

However the disadvantages for microwave applications include:

- very slow with closely-spaced signal frequencies or elements leading to long-time constants;
- no easy method for dealing with frequency-domain data;
- the adaptive time-stepping used reduces FFT accuracy.
More recent research has sought to combine the best features of HB and time-domain within a single simulator technology. Circuit Envelope simulation technology, may be viewed as an extension to HB. In this approach, each of the HB Fourier Series coefficients is considered to be a complex-valued function of time that can represent an arbitrary modulating spectrum around each tone:

\[ v(t) = \sum_{k=-K}^{+K} V_k(t) \cdot e^{j\omega_k t} \]

A time-domain solution is performed consisting of a sequence of HB solutions at each time-step. However, the most critical point is that the transient analysis time-step is determined by the modulation waveform, not by the high-frequency tone(s). Some modifications to standard HB are then required. For example, a linear capacitor now returns a k\textsuperscript{th} harmonic current component given by:

\[ I_k = j\omega_c C \cdot V_k(t) + \frac{d(C \cdot V_k(t))}{dt} \]

The method relies on each signal having a reasonably sparse spectral structure and is particularly suited to non-linear analysis with digitally modulated carriers.

### 3. Discrete Time Convolution

The most fundamental problem in seeking to perform transient analysis at microwave frequencies is the fact that many parts of the systems are only known in the frequency domain, or else much more naturally and conveniently expressed in that domain (typically as S-parameter blocks).

If a way could be found to represent this behavior in discrete time with high accuracy and efficiency, then (using discrete convolution) it would be relatively easy to combine such a description with linear or non-linear time-domain numerical analysis leading to a general high-frequency transient analysis capability.

In fact we have shown that such a technique can indeed be developed, based on an equally spaced sampling in the frequency domain of the S-data for any linear, time-invariant system [4]. Provided sufficient samples are taken up to some maximum frequency fm (corresponding to the highest spectral energy of interest), the discrete time data can interpolate continuously between the original samples leading to high accuracy in transient analysis.

As an example, consider the network of lossy dispersive transmission lines shown in Fig. 1 (representing the input-matching network of a microwave amplifier, for example.

![Fig. 1 Circuit for Discrete Time Representation (lengths ref to 2GHz)](image)

As an example, the discrete time representation of the input reflection coefficient of this network (up to 10GHz) is shown in Fig. 2 together with the exact and interpolated frequency domain responses in Fig. 3.

![Fig. 2 Discrete Time Representation of S11(f) for network of Fig. 1](image)
This analysis involves a full electro-thermal model of the transistor, and Fig. 5 shows the associated transient response of the channel temperature.

**Fig. 5. Transient FET Channel Temperature Response**

### 4. Transient Speed-Up Technique

There are times when the true transient solution is not of particular interest, and so, in a forced single-frequency direct simulation, a great deal of time may pass before the circuit settles into its dynamic steady-state. This is a known disadvantage of transient analysis, but it possible to adapt the approach described in Section 3 to this case.

The method is based on observing that the frequency domain samples need only be taken at the fundamental and at just so many harmonics as are considered to be of interest. The interpolated performance of the resulting discrete impulse responses, will be such as to give an exact representation of the original frequency-domain circuit function at the fundamental and the retained harmonics, although likely to give a very poor representation of the original system function at other frequencies. In the ideal steady state, however, these are the only spectral points of interest.

Besides permitting a very short discrete-time representation, this
approach means that the transient obtained is no longer physically meaningful, but is instead a short ‘pseudo-transient’, which quickly leads in to the desired steady-state solution. Figure 6 shows an example of these two approaches for the same amplifier analysis.

Figure 6 shows an example of these two approaches for the same amplifier analysis. Figure 6(a) gives the true transient output response eventually reaching a steady-state, while Figure 6(b) gives a short but very different ‘pseudo-transient’, much more quickly reaching the steady-state. Note that the final outcome in both cases is the same.

5. Conclusions

A number of issues have been discussed associated with the transient simulation of non-linear microwave systems including arbitrary frequency domain blocks. It is shown that an approach based on discrete time convolution can give excellent results even in demanding applications. This approach can also avoid the problem of long simulation times leading to a steady-state solution by performing a ‘pseudo-transient’ analysis.

6. Acknowledgement

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7. References

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