Simulation of Microwave Communication Circuits and Systems by Envelop and Compressed Transient Methods.

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Abstract

A new technique for the computation of the transient and steady state response of microwave communication circuits is presented. Single or multiple modulated carrier signals can be considered. The modulation may be periodic or aperiodic, and may affect equally, the carrier amplitude, phase or frequency. The major restrictions of the usual simulation techniques (Harmonic Balance and Time Domain Integration) are eliminated.

Introduction

The blow-up of modern microwave mobile communication market requires new simulation capabilities to microwave CAD software. It is particularly necessary to have a convenient mean to carry a thorough transient and steady state analysis of small and medium size sub-systems and systems, under realistic modulated carrier excitation. The modulation may be analog or digital and may affect the carrier amplitude, phase and frequency indifferently.

The two conventional circuit simulation techniques, the Time Domain Integration (TDI) [1] and the Harmonic Balance (HB) [2] do not fulfil these needs. The former is suitable only for circuit analysis in the base-band (i.e. for the modulation signal in the absence of carrier) and the latter for circuit analysis under unmodulated sinusoidal carrier excitation.

Two new techniques called the Envelop Transient (ET) and Compressed Transient (CT) are developed, a combination of which efficiently performs the transient and steady state analysis of microwave circuits for arbitrary modulated carrier excitation.

The Envelop Transient [3] is an extension of the well-known Analytic Signal theory [4] to nonlinear systems. The modulated signal is split in an aperiodic low-frequency dynamic (the envelop or modulation) and a quasi-periodic high-frequency dynamic (the carrier), which are processed separately in a cyclic way.

$$\left\{\begin{aligned} z(t) &= \Re e\left[\sum_{k=0}^{N-1} \hat{Z}_k(t)e^{j\omega_k t}\right] \\ \hat{Z}_k(t) &= \frac{1}{2\pi}\int_{-BW/2}^{BW/2} \hat{Z}_k(\Omega)e^{j\Omega t}d\Omega \end{aligned}\right. \qquad (1)$$

The aperiodic low frequency dynamic is processed by Time Domain Integration and the quasi-periodic high frequency dynamic by Compressed Transient. Every envelop time step, the equivalent time varying circuit seen by the carrier signal is computed by TDI. Then a CT analysis is carried to determine the time varying complex envelop of the signal, as described below.

The Compressed Transient method is a new periodic and quasi-periodic steady-state analysis technique, situated somewhere between the Shooting method and the Harmonic Balance method. It combines the suitability of the HB method to microwave circuits to the per iteration low computation cost of time domain techniques.

The whole process leads to a direct computation of the time varying envelop or modulation of the carrier, with elimination of the main limitations of both HB (number of frequency components) and TDI (ratio carrier over modulation frequency). This makes it is possible to compute in reasonable times, with usual workstations, the transient response of microwave amplifiers, the start up of oscillators (amplitude and frequency), the acquisition of a phase-locked loops, amplitude, phase and frequency (de)modulation, and complex intermodulation factors such as the Noise Power Ratio, independently of the ratio between the largest time constant (biasing elements, high Q filters, narrow band modulation) to the microwave signal period.

Where TDI would need millions of sampling points, ET only needs hundreds of sampling points as the modulation is no more sampled according to the carrier period. Where HB would carry a cumbersome multitone analysis, ET carries only a sequence of simple CT analysis.

We will briefly describe the principle of the new methods, and present some application examples.

The Envelop Transient Principle

Consider the circuit block diagram depicted in Fig.1, where $e(t)$, $v(t)$ and $i(t)$ are respectively the circuit excitation, the voltage and current at the ports of the nonlinear block, and $H(\omega)$ is the transfer function characterising the linear block of the circuit.

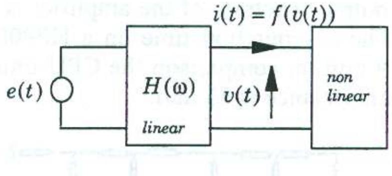

Fig.1 Nonlinear circuit block diagram

Let the various signals be modulated carrier signals described in their complex envelop form as bellow:

$$
\begin{aligned}
e(t) &= \Re e\left[\sum_{k=0}^{N-1} \widehat{E}_k(t)e^{j\omega_k t}\right] \\
v(t) &= \Re e\left[\sum_{k=0}^{N-1} \widehat{V}_k(t)e^{j\omega_k t}\right] \qquad (2) \\
i(t) &= \Re e\left[\sum_{k=0}^{N-1} \widehat{I}_k(t)e^{j\omega_k t}\right]
\end{aligned}
$$

where , $\omega_k = K^T \Lambda$ are linear combinations of independent carrier frequencies $\Lambda_1, \cdots \Lambda_Q$.

Taking separately each carrier frequency component ω_k of the above expressions through the linear filter $H(\omega)$, we find according to the analytic signal theory that circuit of Fig.1 is equivalent to N coupled complex modulation circuits as depicted in Fig.2.

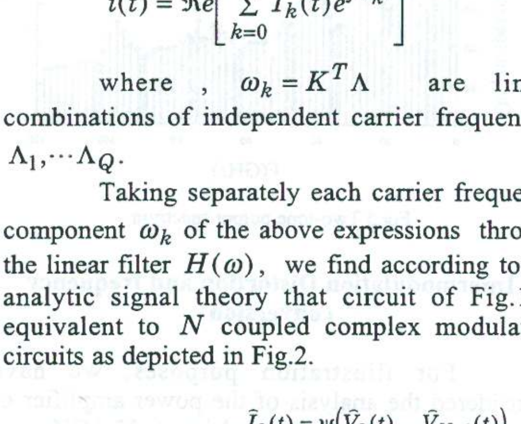

Fig.2 Equivalent complex envelop circuit

The coupling of the equivalent modulation circuits results from the nonlinear block of the circuit. The important feature here is that these equivalent circuits describe only the dynamic of the signal modulations, making abstraction of the carrier frequencies. This gets us rid of the restrictive constraint of having to sample the signal at the carrier rate. Hence the analysis of the modulation circuits is naturally carried in the time domain, where we can efficiently handle the transient and steady state response of any modulation signal.

For a fixed time $t = t_n$ however, we observe that the modulation circuits coupling produced by the nonlinear block, necessitates the computation of a nonlinear quasi-periodic steady state response.

$$
\begin{cases}
\widehat{V}_k(t_n) = Y_k \widehat{I}_k(t_n) + Eq_k(t_n) \\
k = 0, \cdots, N-1 \\
\\
i(t) = f(v(t))
\end{cases}
$$

Thus we see that the Envelop Transient method results to the analysis in the time domain of a complex modulation circuit , in which every time step a carrier frequency periodic or quasi-periodic steady state is computed, as sketched in Fig.3. For the maximum efficacy of the Envelop Transient process, it is therefore necessary to have a powerful method for carrying carrier frequency periodic and quasi-periodic steady state analysis. Nowadays this analysis is usually done by Harmonic Balance. Unfortunately this technique cannot efficiently handle large number of harmonics and multiple tones. We present hereafter a new technique called Compressed Transient, more suitable for this purpose.

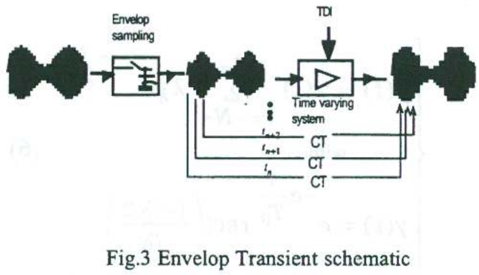

Fig.3 Envelop Transient schematic

The Compressed Transient Principle

As stated above, the Compressed Transient technique is designed to solve the a nonlinear system of the general form

$$
\begin{cases}
V_k = Y(\omega_k) I_k + Eq_k \\
k = 0, \cdots, N-1 \\
\omega_k = K^T \Omega \qquad (3) \\
\\
i(t) = f(v(t))
\end{cases}
$$

For sake of clarity, let us consider the case of a periodic steady state response, i.e. $\omega_k = k\Lambda_0$. Instead of solving directly the above equation by the Harmonic Balance technique, the Compressed Transient consists of transforming this discrete frequency domain equation into a time domain equation of the form

$$\begin{cases} v(t) = \bar{y}(t) \otimes i(t) + eq(t) \\ t \geq 0 \\ i(t) = f(v(t)) \end{cases} \quad (4)$$

with the condition that $\bar{y}(t)$ is a short causal impulse response satisfying the steady state mapping condition:

$$\begin{cases} \bar{Y}(\omega_k) = Y(\omega_k) \\ k = 0, \cdots, N-1 \\ \bar{Y}(\omega) = \int_0^{\infty} \bar{y}(t) e^{j\omega t} dt \end{cases} \quad (5)$$

If such an impulse response can be found, then the steady state response obtained from (4) is the solution of (3). Moreover, if the duration of the impulse response is short compared to the period of the steady state response, then the steady state of eq (4) will be obtained after a few period of the excitation signal. Hence the computation cost of the Compressed Transient small compared with Harmonic Balance.

We have found that the impulse response family below

$$\begin{cases} \bar{y}(t) = \gamma(t) \sum_{k=-N+1}^{N-1} \lambda_k e^{j2\pi k \frac{t}{T_0}} \\ \text{with} \\ \gamma(t) = e^{-\alpha \frac{t}{T_0}} \operatorname{rect}\left(\frac{t - T_0/2}{T_0} \right) \end{cases} \quad (6)$$

satisfies the above requirements with a good efficiency. In the above expression $T_0 = \frac{2\pi}{\Lambda_0}$ is the period of the steady state regime and α is a free argument which controls the decay of the impulse response for $t > 0$. The larger α, the shorter will be the effective impulse duration. The optimum value of α is about 10 for a two order numerical integration scheme in eq (4). Larger values of α need to consider higher order numerical integrations. For $\alpha = 0$ the impulse response does not decay with time and equation (4) is just the discrete Fourier transform of eq (3). This corresponds to the dual time domain form of the Harmonic Balance and is known as the Waveform-Balance or convolution equation [5].

Application Examples

Two tone amplifier analysis

To show the efficiency of the Compressed Transient method, we have performed a two-tone analysis of the four stage 2-18 GHz MMIC distributed amplifier depicted in Fig.4. The two independent tones are 12.1GHz and 14GHz. The number of harmonics considered for each tone was 8. The output spectrum of the amplifier is given in Fig.5. The computation time on a HP9000 series 700 is 9 min, in comparison the CPU time for the Harmonic Balance is 53 min.

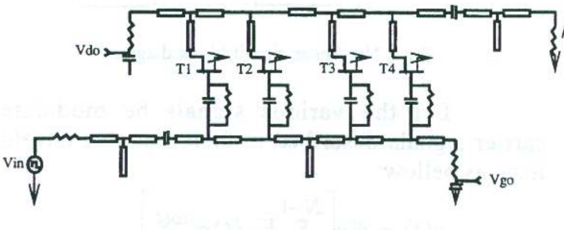

Fig.4 2-18GHz MMIC Distributed Power Amplifier

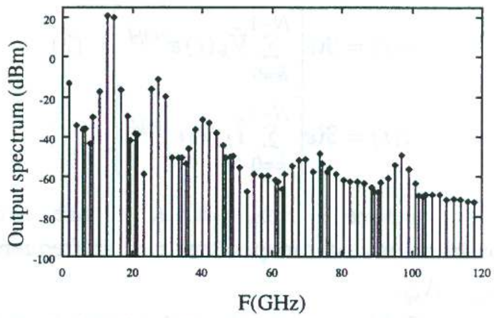

Fig.5 Two-tone output spectrum

Intermodulation Distortion and frequency conversion

For illustration purposes, we have considered the analysis of the power amplifier of Fig.4 for a two-carrier signal input, 12.1GHz and 14GHz. The 12.1GHz carrier is unmodulated while the 14GHz carries a triangular modulation.

Fig.6(a), (b) and (c) show the amplifier output spectrum around the two input carrier frequencies and the beat frequency 1.9GHz, respectively. We may observe the intermodulation contribution to the unmodulated 12.1GHz carrier and also the down frequency conversion from the modulated 14GHz carrier to 1.9GHz.

A number of 5 harmonics per independent carrier frequency was considered in the simulation. The CPU time is 10 min.

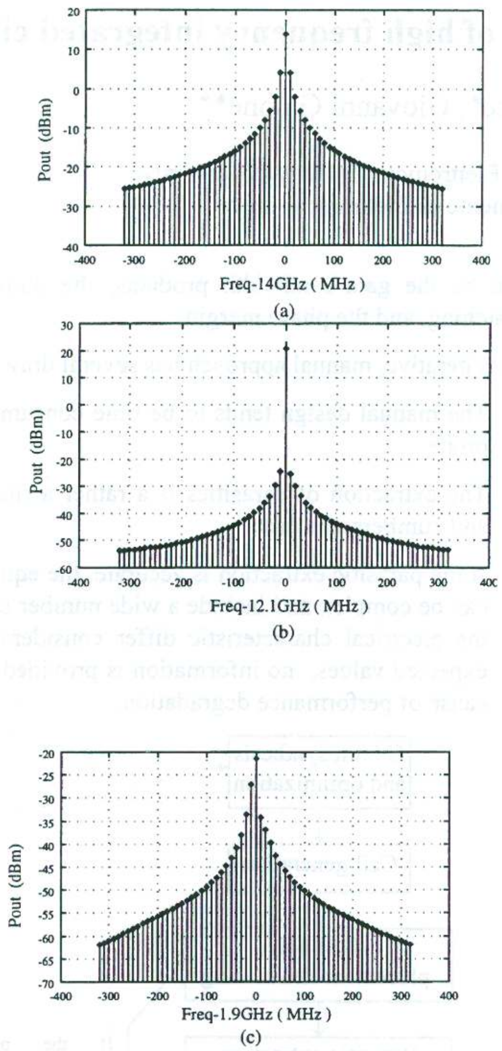

Fig.6 Amplifier output spectrum
(a) Output spectrum around the modulated carrier (14GHz)
(b) Output spectrum around the unmodulated carrier (12.1GHz)
(c) Output spectrum around the beat frequency (1.9GHz)

Inter-channel distortion by Noise Power Ratio

Envelop Transient is a suitable tool for computing the intermodulation distortion of adjacent communication channels in a power amplifier. Especially it can efficiently perform computation of the figure of merit that is the Noise Power ratio (NPR). The test signal for NPR computation is shown in Fig.7(a), we have computed the output spectrum of the amplifier of Fig.4 to this test signal. The result is drawn in Fig.7(b), where we may see how the initially notched middle channel is filled by the intermodulation contribution of the adjacent channels.The CPU time is 24 min

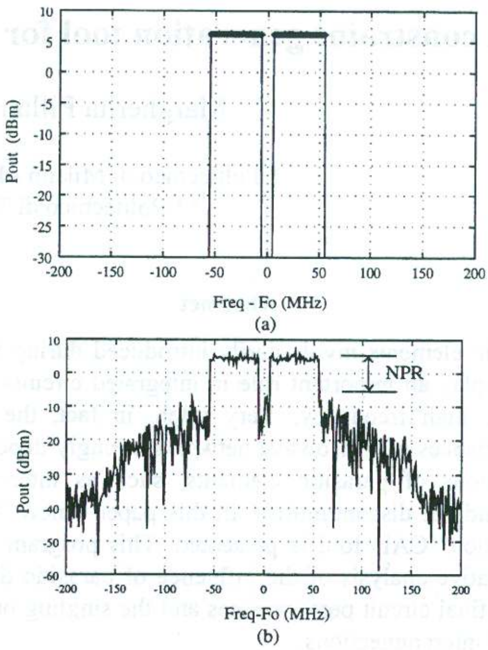

Fig.7 Amplifier Input and Output spectrum

Conclusion

New simulation techniques for the analysis of microwave communication circuits have been presented. These allow to compute in reasonable times, with usual workstations, the transient and steady state response of microwave circuits with multiple modulated carrier excitation. A important amount of computation time and memory saving is obtained with respect to the previous methods.

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