A New Circuit Envelope Simulation Technique  
for Analysis of Microwave Circuits

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Abstract—This paper proposes to use variable time steps in  
circuit envelope simulation. The circuit envelope is a general-  
purpose simulation technique for the transient and steady  
state analysis of microwave communication systems and  
circuits. When a microwave circuit is excited with a time  
variant envelope signal as digital modulated signal, circuit  
envelope simulation method may be used. In this paper a new  
technique is proposed to improve the efficiency of the circuit  
envelope simulation. Using this technique, a millimeter wave  
power amplifier is simulated and its results are presented. The  
evaluation of the results with the existing literature proves the  
accuracy and efficiency of the new technique.

Index Terms—Circuit envelope, nonlinear circuit,  
harmonic balance, millimeter wave.

I. INTRODUCTION

The modern communication systems employ  
sophisticated digital modulations, such as QPSK,  
GMSK, and QAM, and to improve the spectral efficiency  
[1]. These modulated signals are wideband and time  
variant. The simulation results obtained by the frequency  
domain techniques are not sufficient to present all  
characteristics of these modulated signals and it is required  
to employ time domain methods [1], [2]. In the absence of  
the effective and general-purpose techniques that can  
conveniently handle transient and steady state analysis of  
nonlinear circuits for modulated carrier excitation, the  
circuit envelope (CE) provides reduction in simulation  
time, and the memory usage [3]-[5].

The circuit envelope method can be efficiently used to  
study a wide range of microwave and millimeter wave  
circuits, such as power amplifiers, PLLs, and oscillators.  
We try to increase the efficiency of CE method by using  
variable time-steps.

In this paper after presenting the circuit envelope  
method, we develop the idea of the variable time-steps  
method. Finally, we design and simulate a typical Ka band  
power amplifier based on this approach.

II. THE CIRCUIT ENVELOPE METHOD

The CE method provides a middle solution between time  
and frequency domain methods [1], [2]. This method,  
which is developed on the basis of time dependent Fourier  
transforms, generally uses time domain techniques over  
frequency domain analysis [3], [6], [7].  

Using complex variable concept, the fundamental signals  
and their envelopes are assumed complex and the time  
domain signals can be obtained from their real part.

If we consider a modulated signal, then the signal  
x(t) in the circuit may be written as

\[ x(t) = \text{Re} \left( \sum_{k} \hat{x}_k(t) e^{j \omega_k t} \right) = X^T(t) \cdot \alpha(t) \]  

where

\[ \hat{x}_k(t) = \frac{1}{2\pi} \int_{-\pi/2}^{\pi/2} \hat{x}_k(\Omega) \cdot e^{j \Omega t} d\Omega \]  

\[ \hat{x}_k(t) \] is time variant complex envelope of the \( k \)-th  
harmonic of carrier frequency \( \omega_0 \), BW is the largest  
bandwidth of the carrier frequency envelopes [5]-[8], and

\[ \alpha(t) = \begin{bmatrix} 1 & e^{j \omega_0} & \cdots & e^{j (N-1) \omega_0} \end{bmatrix}^T \]  

where \( \alpha(t) \) is the Fourier basis vector and \( \hat{x}_k(t) \) is  
the vector slow varying Fourier coefficients or the envelope  
components

\[ X(t) = \begin{bmatrix} \hat{x}_0(t) & \ldots & \hat{x}_{K-1}(t) & \hat{x}_K(t) \end{bmatrix} \].  

Using a circuit consisting of sources, nonlinear RC, and  
linear RLC elements, the modified nodal analysis in a node,  
e.g., node \( m \), leads to a nonlinear differential equations of the form

\[ \frac{d}{dt} q_m(v(t)) + i_m(v(t)) + i_{m,n}(v(t)) + i_{n,m}(v(t)) = 0 \]  

where \( v(t) \) is the vector of node voltages; \( i_m \), is the  
vector of the source contributions; \( i_{m,n} \), is the vector  
of the linear part of the circuit \( i_m \), and \( q_m \) define the  
contributions of nonlinear reactive and conductive  
elements, respectively.

A solution as \( v(t) = V^T(t) \cdot \alpha(t) \) is desirable, and it  
is assumed that all the signals in the circuit have the same  
form as \( x_m(t) = X^T_m(V(t)) \cdot \alpha(t) \).

When \( \alpha(t) \) is applied to each node, it forms a system of  
nonlinear differential equations, which is shown in the  
following matrix notation

\[ \frac{d}{dt} Q^T(t) + j \Omega \cdot Q = I(t) \]  

\[ Q^T(t) \] and \( \Omega_m \) is defined as \( \text{diag}(\text{diag}(0 \omega \cdots K \omega)) \).

After sampling (6) at \( t_i \) moments, we have

\[ \frac{d}{dt} Q^T(t) + j \Omega \cdot Q = I(t) \]  

where the dimension of current vector is \( N(K+1) \times 1 \).
where $V_i = V(t) = V(t + \Delta t)$.

Assuming that envelope variation is changing slowly, we may assume $Y(\omega) = Y(\omega + \Delta \omega)$. Accordingly, $I'_{s}(V_i')$ term can be replaced from frequency domain relations [3], [4], [7]

$$I'_{s}(V_i') = Y \cdot V_i'$$

(8)

It is assumed for each $t_i$, the following approximation is valid [3]

$$\left. \frac{d}{dt} Q'V(t) \right|_{t_i} = \alpha_i Q'V(t_i) + \beta_i$$

(9)

Using these assumptions, (8) is changed as follows

$$I'_{s}(V) + \alpha_i Q'V(t) + j \beta \sum_{i} Q'V(t_i) + \beta_i$$

(10)

Above vector equation is a system of harmonic balance equations, which can be solved for $V_i$ at every time step $t_i$. In each envelope time step, a HB analysis must be carried out [2]. Using inherent advantage of the envelope approach, the time step spacing needs only to be small enough to resolve the envelopes around each.

### III. VARIABLE TIME STEPS

The idea of variable time steps is based on finding and removing unnecessary time-steps.

The idea may be presented as follow by recalling (6), (9)

$$\left. \frac{d}{dt} Q'V(t) \right|_{t_i} = j \Delta \sum_{i} Q'V(t_i) + I'_{s}(V_i') + \beta_i I'_{s}(V_i') =$$

(11)

$$\left. \frac{d}{dt} Q'V(t) \right|_{t_i} = \alpha_i Q'V(t_i) + \beta_i$$

(12)

Equation (12) can be reevaluate as follow

Using these assumptions, (12) is changed as follows

$$I'_{s}(V_i') + j \beta \sum_{i} Q'V(t_i) + \beta_i$$

(13)

It can be seen that if $Q(t_i) = Q(t_{i+1})$ and $I'_{s}(t_i) = I'_{s}(t_{i+1})$, then (11) converts to a common Harmonic Balance (HB) equation.

In this case it is not required to solve the equation for $i+1$ step if $I'_{s}(t_i) = I'_{s}(t_{i+1})$. This means that we can assume $\Delta t$ small enough to follow the input transient effects precisely and after ending transient effects, we can use a HB instead of many CE routines. The improvement in efficiency may be observed in some circuits more clear than others, e.g., PLLs transient responses can be efficiently observed using this technique.

### IV. POWER AMPLIFIER DESIGN

In this section a Ka band class A power amplifier with 13 dB gain, 18 dBm output power and bandwidth of 2 GHz is designed at 28 GHz center frequency. A Pseudomorphic InGaAs/AlGaAS/GaAs HEMT technology is selected due to its high cutoff frequency and high current density [8].

The schematic of power amplifier is illustrated in Fig. 1. In Fig. 2 the output curve is presented for the input of 0 dBm in different frequencies using ADS2002. The Fig. 3 compares the ADS2002 simulation results with the results of the authors’ software.

### V. SIMULATION RESULTS

The circuit has been examined when excited by $4\pi$ QPSK modulated signal at 28 GHz center frequency and 1 GHz bandwidth. For this purpose, we perform CE method for single transistor circuits. The circuit envelope simulation has been implemented for this scenario.

In the first step, the ADS2002 simulation results are compared with the results of the authors’ software in Fig. 4. The results show that accuracy of authors’ classical circuit envelope simulation routine.

In Fig. 5 the output envelope signals using classic CE and variable time-step CE are traced. As it is demonstrated, the these two methods result the same output envelope signals.
Comparing the simulation time and steps, it can be seen that employing variable time steps improve the simulation time. It should be noted that this improvement depends on the input signal. Table I presents the simulation time and steps of these two.

VI. CONCLUSIONS

A new CE method, using variable time steps, has been presented. This method can improve the simulation efficiency by eliminating unnecessary time steps. As mentioned, the improvement depends on how the time step has been selected, and the kind of input signal that applied. From the simulation results, it can be seen that the presented method can be effectively used in simulating circuits and systems in which small duration transient response is important but most of the time the circuit or the system are working in their steady state conditions.

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REFERENCES


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