Tool for efficient intermodulation analysis using conventional HB packages

G. Vannini, F. Filicori and P. Traverso

A simple and efficient approach is proposed for the intermodulation analysis of nonlinear microwave circuits. The algorithm, which is based on a very mild assumption about the frequency response of the linear part of the circuit, allows for a reduction in computing time and memory requirement. Moreover, it can be easily implemented using any conventional tool for harmonic-balance circuit analysis.

Introduction: The intermodulation (IM) analysis of microwave integrated circuits which include several active devices represents a computing intensive task owing to the large number of harmonic components which must be taken into account in the harmonic-balance (HB) algorithm [1, 2]. This is particularly true when the number of unknowns is very large as in the case of complex circuits operating under multitone excitations (e.g. IM prediction).

Different techniques have been proposed [1 – 5] for the efficient and accurate HB-based multitone analysis of nonlinear microwave circuits. However, the algorithms developed are usually quite complex and, above all, their implementation requires access to the source code of the HB programme.

In this Letter, an algorithm is proposed for the fast and accurate IM analysis of microwave circuits. It is based on a modification of a previously proposed approach, the 'frequency-windowing HB' (FWHB) [3], which allows for its implementation using any conventional (commercially available) HB programme without the need for more complex and expensive special-purpose CAD tools [4].

FWHB algorithm: As an example, to introduce a simple mathematical notation for the algorithm description, the elementary circuit in Fig. 1 will be considered. This is composed of a nonlinear element, characterised by its current/voltage characteristic $i = F[v(t)]$, connected to a linear network which is described by means of its equivalent admittance Y and current source S.

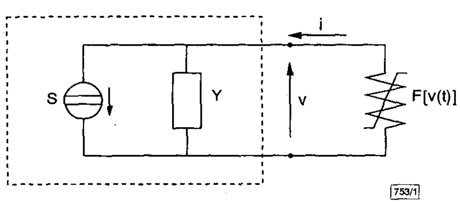

Fig. 1 *Nonlinear circuit composed of linear network connected to nonlinear conductance*

The algorithm is based on a suitable representation of signal spectra suggested by the fact that when narrowband, multitone excitations are considered, the spectrum of $v(t)$ is strongly nonuniform. More precisely, in the IM analysis of amplifiers or mixers, the signal sources are composed of two/three or more RF sinusoidal excitations characterised by commensurable frequencies (i.e. a minimum common multiple period T, although usually very long, does exist) plus (in the mixer case) an LO oscillator source at a frequency which is not practically commensurable with the RF sources. Under such conditions, several spectral components of $v(t)$ are grouped in narrow frequency intervals, and each interval is relatively far from the nearest interval, so that we can conveniently write

$$v(t) = \sum_{p=-P}^{P} \sum_{h=-H}^{H} V_{p,h} e^{j(\omega_p + h\Delta\omega)t} \qquad (1)$$

where $V_{-p,-h} = V^*_{p,h}$, $\omega_{-p} = -\omega_p$ (being $\omega_0 = 0$ and $\Delta\omega = 2\pi/T$). In eqn. 1 the signal $v(t)$ is expressed by introducing $P + 1$ 'frequency windows', each one including $2H + 1$ spectral components; the angular frequencies are uniquely identified by means of suitably chosen 'carrier frequencies' ω_p (which are not necessarily in a harmonic relation) and associated 'displacements' $h\Delta\omega$.

By imposing the current equilibrium at the connection port between the nonlinear element and the linear network in Fig. 1 and using eqn. 1, the FWHB problem can be expressed in the following form:

$$\begin{aligned} I_{p,h} &= \mathbf{F}_{p,h}\left\{ F\left[\sum_{p=-P}^{P} \sum_{h=-H}^{H} V_{p,h} e^{j(\omega_p + h\Delta\omega)t} \right] \right\} \\ &= Y_{p,h} V_{p,h} + S_{p,h} \\ p &= 0,1,\ldots,P \quad \begin{cases} h = 0,1,\ldots,H & P = 0 \\ h = -H,\ldots,+H & P \neq 0 \end{cases} \end{aligned} \qquad (2)$$

where $S_{p,h}$ and $Y_{p,h}$ are the spectral components of the equivalent source and the values of the linear admittance at $\omega_p + h\Delta\omega$, while $\mathbf{F}_{p,h}$ is the Fourier operator providing the corresponding spectral component $I_{p,h}$ of $i = F[v(t)]$.

By introducing an auxiliary time variable τ associated with the period T, the definition of $v(t)$ in eqn. 1 can be, more conveniently, expressed in the form

$$v(t,\tau) = \sum_{p=-P}^{P} V_p(\tau) e^{j\omega_p t} \quad \text{with } V_p(\tau) = \sum_{h=-H}^{H} V_{p,h} e^{jh\Delta\omega\tau} \qquad (3)$$

It is interesting to observe that the second of eqn. 3 describes the spectrum within each frequency window in the form of a 'slowly' modulated signal by means of a complex-envelope-like formulation.

If the bandwidth $2H\Delta\omega$ of the frequency windows is small enough with respect to the corresponding variation of the linear network admittance, as usually happens in IM analysis, $Y_{p,h}$ can be reasonably approximated [3] by a constant value $Y_{p,h} \simeq \tilde{Y}_p = Y(\omega_p)$. Under these conditions, it can be shown that, by using a representation of the type of eqn. 3, the HB equations (eqn. 2) can be rewritten, for any value of τ, in the approximated form

$$\mathbf{F}_p\left\{ F\left[\sum_{p=-P}^{P} V_p(\tau) e^{j\omega_p t} \right] \right\} \simeq \tilde{Y}_p V_p(\tau) + S_p(\tau)$$
$$p = 0,1,\ldots,P \quad 0 \leq \tau \leq T \qquad (4)$$

In this new formulation a number N_τ of τ-'decoupled' HB problems (eqn. 4) involving only $P + 1$ spectral components must be solved instead of the single problem (eqn. 2) of larger dimensions $P \times (2H + 1) + H + 1$. More precisely, the solutions of eqn. 4 for a given set of values of τ provide samples of the complex envelopes $V_p(\tau)$ which can be used, by applying a discrete Fourier transform algorithm consistently with the definition of eqn. 3, to compute the required spectral components $V_{p,h} = \mathbf{F}_h\{V_p(\tau)\} = 1/N_\tau \Sigma_{k=0}^{N_\tau-1} V_p(\tau_k)e^{-jh\Delta\omega\tau_k}$. To this end, a number $N_\tau = 2H + 1$ of uniformly spaced τ-samples, according to the Nyquist criterion, are required. Since CPU time and memory occupation in HB analysis grow more than linearly with the number of spectral components, it should be evident that N_τ solutions of eqn. 4 are computationally less expensive than directly solving eqn. 2.

Clearly, the constant admittance approximation introduced in the HB equations, which enables the results of different HB analyses to be considered as decoupled in the τ domain, may influence the accuracy of the solution; however, as confirmed by simulation results, the loss of accuracy is totally negligible in IM analysis since the frequencies of the sinusoidal excitations adopted as test signals are normally chosen so close as to make the constant admittance approximation completely justified.

Implementation and validation: The implementation of the FWHB algorithm in the framework of an HB tool simply requires the execution of a number N_τ of conventional HB analyses and a post-processing programme which applies a Fourier transform algorithm to the N_τ τ-domain samples obtained. The HB conventional analyses can be easily carried out by sweeping (a sweeping facility is usually available in any HB tool) the auxiliary time variable τ which controls a suitably defined, complex-envelope source $S(\tau)$. For instance, in the case of a two-tone IM test with frequencies $\omega_1 - \Delta\omega$ and $\omega_1 + \Delta\omega$, the equivalent source in eqn. 2 is composed only of the two spectral components $S_{1,-1}$ and $S_{1,1}$. Consequently, the complex-envelope source $S_1(t)$, at the carrier frequency ω_1, to be used in the conventional HB analyses is defined as

$$S_1(\tau) = (S_{1,1} + S_{1,-1})\cos(\Delta\omega\tau) + j(S_{1,1} - S_{1,-1})\sin(\Delta\omega\tau) \qquad (5)$$

The FWHB algorithm has been implemented in the Hewlett-Packard MDS programme for microwave circuit analysis. In particular, the results of the conventional HB analyses in the τ-domain are stored in a standard MDS dataset, the contents of which are passed to a C-language programme which performs the final Fourier transform required. Finally, the analysis results are stored in a new dataset for the presentation. The DDL (design database language) has been adopted to transfer data from/to MDS datasets and the C programme. This enables the whole procedure to be transparently performed within the MDS environment. When a high-level design language (DDL) is not available, the whole procedure can still be implemented by using input/output files to transfer data between the HB simulator and the external C programme.

Validation tests were carried out on the dual-gate FET mixer available in the demonstration files of MDS. In particular, two-tone IM analyses (f_{LO} = 13GHz, f_{RF1}, f_{RF2} = 10GHz ± 5MHz) were performed both by using MDS and the MDS/FWHB algorithm. In this case, the proposed algorithm requires a number N_τ of conventional two-tone HB analyses where the two RF frequencies are replaced by a source $S_1(\tau)$ defined as in eqn. 5.

On an HP715 workstation with 64Mbyte RAM, the mixer IM analysis with MDS was feasible only with a simple spectrum (justified only for a relatively low level of nonlinearity) characterised by three harmonics for the LO and RF frequencies and a maximum order of IM products equal to 9 (a total of 172 spectral components). The results obtained using FWHB/MDS were coincident with those provided by MDS, but with a relevant reduction in CPU time and memory requirements (44 compared with 479s and 5.2 compared with 61.3Mbyte).

Using the FWHB/MDS algorithm more complex spectra (reasonably necessary with higher level of nonlinearity) can also be handled. For instance a three tone IM analysis of the same mixer was carried out with 20 LO harmonics (a total of 1184 spectral components) with an acceptable, considering the problem complexity, CPU time of 20min.

Finally it must be observed that, for the particular case of IM analysis, the FWHB performance is excellent also with respect to highly powerful, more complex general-purpose algorithms [5]. For instance a three tone IM analysis (for a total number of 579 spectral components) of a nine FET distributed amplifier under strongly nonlinear operation was carried out in 1312s and with 18.9Mbyte of memory. These figures, although not directly comparable with the numerical effort reported in [5] for the three tone analysis of a similar circuit (1982s and 68Mbyte), give a clear indication of the FWHB efficiency.

To conclude, a simple and efficient approach, which can easily be implemented in any conventional HB tool, has been proposed for the intermodulation analysis of nonlinear microwave circuits. The algorithm enables quite complex circuits and spectra to be easily handled also on conventional workstations and, for the specific case of IM analysis, requires a numerical effort reasonably comparable with that of other more complex algorithms [5] based on a proprietary software. (More details on the MDS implementation can be found in the http page www-micrel.deis.unibo.it/eletlc.)

Acknowledgment: This work was partly supported by the European Space Agency ESA/ESTEC.

16 June 1999

Electronics Letters Online No: 19990941
DOI: 10.1049/el:19990941

G. Vannini (*Department of Engineering, University of Ferrara, Via Saragat 1, 44100 Ferrara, Italy*)

F. Filicori and P. Traverso (*Department of Electronics, Computers Science and Systems, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy*)

References

1 FILICORI, F., and MONACO, V.: 'Computer-aided design of nonlinear microwave circuits', *Alta Frequenza*, 1988, **57**, (7), pp. 355–378

2 RIZZOLI, V.: 'State-of-the-art harmonic-balance simulation of forced nonlinear microwave circuits by piecewise technique', *IEEE Trans.*, 1992, **MTT-40**, (1), pp. 12–28

3 FILICORI, F., MONACO, V., and VANNINI, G.: 'Computationally efficient multitone analysis of nonlinear microwave circuits'. Proc. 21st EuMC, September 1991, pp. 1550–1555

4 HP EEsof MDS Manual, v7.0, Designer's Task Ref. Vol.4, Circuit Envelope Simulation, July 1996

5 RIZZOLI, V.: 'Fast and robust inexact Newton approach to the harmonic-balance analysis of nonlinear microwave circuits', *IEEE Microw. Guid. Wave Lett.*, 1997, 7, (10), pp. 359–361

Adaptive bit loading scheme using COFDM at low elevation over LEO satellite communication channel

Lei Wan, I.G. Gosling and V.K. Dubey

Much interest has been shown in employing LEO satellite communication systems. A novel algorithm is proposed for adaptive bit loading (multilevel modulation assignment) between COFDM subcarriers in a frequency selective fading channel. Two-dimensional alignment has been carried out. The system performance is greatly improved at low elevation angles compared to that using fixed bit loading. Furthermore, the comparison shows that this adaptive bit loading COFDM system is suitable for frequency selective slow fading channels, which have time-varying deep nulls in the frequency response.

Introduction: The OFDM (orthogonal frequency division multiplexing, also named orthogonal multi-carrier modulation, MCM) transmission method was first introduced about three decades ago [1]. With some early obstacles removed, such as the need for a high speed real time fast Fourier transform chip, and relatively large linear range required for the RF power amplifiers, adaptive bit loading COFDM has emerged as a candidate for multipath fading LEO (low Earth orbit) communication channels, and has attracted attention recently. Although some existing loading algorithms have been used for asymmetric digital subscriber lines (ADSLS) and coaxial copper lines [2], it has been found that, with some modifications, it is very suitable for time varying multipath fading channels.

In this Letter, we first describe the LEO channel phenomena at low elevation angle, and the COFDM system. While explaining and optimising the mechanism of the adaptive bit loading scheme, we show that the performance of the system can be improved by almost 6dB and even more when E_b/N_o > 20dB, with a loss of only 5% of capacity for bits used by the channel estimator.

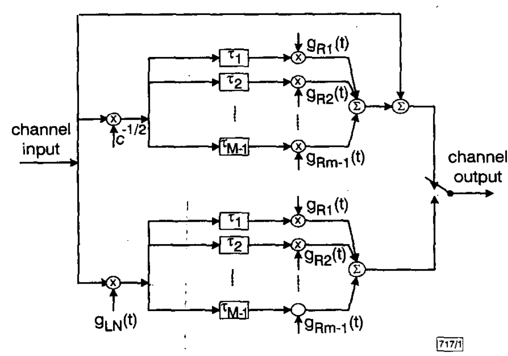

Fig. 1 *LEO channel model in urban area*

Satellite channel model: Here we consider the worst case of the LEO satellite channel. This condition occurs at low elevation angles, with many significant multipath components. The nonstationary model for urban area (by Lutz *et al.* [3]) has been followed. The model is based on a two-state Markov process, where the fading is switched between a Rice process (good channel state) and a Rayleigh-lognormal process (bad channel state). The lognormal and Rayleigh processes are multiplicative. The Jakes model was adopted to generate Rayleigh distributed tap-delayed multipath components. The parameters were calculated at 10°