NEURAL NETWORK APPROACH FOR THE CHARACTERISATION OF THE ACTIVE MICROWAVE DEVICES

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Abstract

Small-signal and noise behaviour of an active microwave device is modeled through the neural network approach for multiple bias/configurations. Here, the device is modelled by a black box whose small-signal and noise parameters are evaluated through a neural network, based upon the fitting of both of these parameters for the multiple bias or configuration. The concurrent modelling procedure does not require to solve device physics equations repeatedly during optimization. Compared to the existing device modelling techniques, the proposed approach has the capability to make high-dimensional models for highly nonlinear devices.

I. INTRODUCTION

Aim of the work

The aim of this work is to model a microwave transistor by a black-box for which small-signal and noise parameters are evaluated through a neural network, based upon the fitting of both of the parameters to the operational bandwidth for multiple bias of various types of configuration. So the stages of the work can be ordered as follows:

(i) Establish a novel neural network of feedforward type with a single hidden layer,

(ii) using back-propagation and nonlinear types of activation functions, train the network for both the signal-noise behaviours over the operational bandwidth for multiple bias and multiple configuration of any type of microwave transistor,

(iii) Establish performance measure of the model,

(iv) Predict the small-signal and noise behaviours at any operation frequency around any bias condition of any type of configuration using the neural network which has already been trained to make functional approximations of the intrinsic device nonlinear characteristics in the vicinities of the chosen bias points.

From the classical point of view, a unified small-signal-noise equivalent circuit for a microwave transistor can be divided into two parts: extrinsic circuits and intrinsic circuit. The intrinsic circuit characterize the active region under the gate (or base) whose parameters are functions of bias condition and device technological parameters, whereas the extrinsic parameters depend at least to a first approximation only on the technological parameters. If an unified circuit for a MESFET is considered, the most important extrinsic parameters are the gate, source and drain inductances due to the bond wires and the gate, source and drain resistances. The four main intrinsic parameters are the input capacitance \(C_{\text{gs}}\), the transconductance \(g_m\), the output conductance \(g_d\) and the feedback capacitance \(C_{\text{gd}}\). In addition, the electrical behaviour of the intrinsic device requires the introduction of two more parameters. The intrinsic resistance \(R\), which can be related to distributed nature of the RC input network, and the delay \(\tau\), which is introduced in the expression for the current generator and corresponds to the time needed for the carriers to travel under the gate.

Briefly due to the intrinsic and extrinsic device properties, both the signal and noise parameters are functions of the bias conditions, frequency, configuration type. The way to approximate these functions in the literature so far is considered in the forthcoming subsection.

Review the literature

The problem of approximating measured device parameters or device response has been formulated as an optimization problem with respect to the equivalent circuit of a proposed model. The traditional approach in modeling is almost entirely directed at achieving the best possible match between measured and calculated parameters. This approach has serious shortcomings in two frequently encountered cases. The first case is when the equivalent circuit parameters are not unique with responses selected and the second is when the nonideal effects are not modeled adequately, the latter causing an imperfect match even if small measurement errors are allowed for. In both cases, a family of solutions for circuit model parameters may exist which produce reasonable and similar matches between measured and calculated responses. Besides, published literature is concerned with the equivalent circuit for the single-bias which are only either small-signal models or the noise behaviour descriptions based on existing signal equivalent circuits that have nothing to do with the device noise characteristics. In [1] and [2] these two behaviours are combined in an unified classical circuit model for only a single-bias. A recent work [3] combines the signal and noise parameters in an neural network model over the fairly large operation band at a single bias point.

II. NEURAL NETWORK MODEL

Signal-Noise Behaviour of a Microwave Transistor

S and N parameter data measured at the multiple bias conditions \((V_{\text{ds}},I_{\text{ds}})\) for the configuration
types (0.2,0.5,0.8) is all used to train the neural net. The amount of data used in the training and iteration number are altogether optimised against the error. The measured S and N parameter data around a bias point for a type of configuration can be arranged in a table-form function as follows:

\[
\begin{array}{c|c|c}
S^{(1)} & N^{(1)} \\
S^{(2)} & N^{(2)} \\
\vdots & \vdots \\
S^{(N)} & N^{(N)} \\
\end{array}
\]

\[\text{where } S^{(1)}, N^{(1)}, \ldots, S^{(N)}, N^{(N)} \text{ are respectively, the scattering and noise vectors at the f_1, \ldots, f_N measurement frequencies.}
\]

After having completed the training process, the performance vectors S^{(k)}, N^{(k)} at a desired frequency f_k at the conditions (V_{CE}, I_{C}, CT or V_{DS}, DS, CT) for any configuration type among the trained ones can be obtained from the network output by inputing the frequency f_k bias configuration type which is defined by the numbers (0.2, 0.5, 0.8). If S^{(N)}, N^{(N)} are unmeasured they are determined by the generalization process of the neural network, which can be considered as the ability of the network to give good outputs to inputs it has not been trained on. In our application, the signal-noise neural network can generalize the performance not only at a single operation frequency of the trained bias condition at the whole operation band of the untrained bias condition. The first may be named as the single frequency generalization, while the latter is called whole band generalization. Examples of which will be given in the result section.

The multi-bias and configuration signal-noise neural network

We use a novel neural network of feedforward type with a single hidden layer having the same number of nodes as the output layer. Let n, N_h and N_o be respectively the number of nodes in the input, hidden and output layers. In the signal-noise neural network n=4 with the frequency, bias condition and the type of configuration CT, N_h=N_o=12 which are the signal and noise vectors given by (2). (Fig. 2)

The signal resulted from the hidden layer to the ith output node can be expressed in the form of

\[\Phi_i(x, T_i, W, \theta_h) = \sum_{k=1}^{N_h} T_{hi} \phi_k(x, W_{hi}, \theta_h)\]

and the net output of the ith output node is obtained as follows

\[\phi_k(x, T_i, W, \theta_h) = V_i f_k(\Phi_1 + \Theta_i)\]

where \(\phi_k\) and \(f_k\) are the basis functions for the hth hidden node and the ith output node, respectively, which are sigmoid type of nonlinear functions in our case, e.g. \(\phi_k(W_{hi}, x)\) can be expressed in the following form:

\[\phi_k(x, W_{hi}, \theta_h) = \frac{1}{1 + \exp(-\sum_{i=1}^{N} x_i W_{hi} - \theta_h)}\]

In equations 3-5, x is the input vector of n dimensions:

\[x=[x_1, x_2, \ldots, x_n]^T\]

\[T_i \text{ is the weighting vector between the ith output node and the hidden layer.}\]

\[\theta_h, \Theta_i \text{ are the local memories belonging to the hth hidden and ith output nodes, respectively. In the eqn. (4) V is the weighting factor of the output layer:}\]

\[V=[V_1, V_2, \ldots, V_{N_k}]^T\]

\[\text{Determination of the network parameter matrix P}\]

If parameters of the network architecture is denoted \(P\), the network parameter matrix \(P\) will have \(N_h N_o + N_h N_i + N_o\) elements which consist of weighting factors between the input and hidden layers and the hidden and output layers, the local memories of the hidden and output nodes. The training process can be defined as computation of the network parameter matrix \(P\) so that the error function which is

\[E(P) = \frac{1}{2} \sum_{k=1}^{N_k} \left( y_{j}^{(k)} - \Phi_{j}^{(k)} \right)^2\]

is minimised, where \(y_{j}^{(k)}\) and \(\Phi_{j}^{(k)}\) are respectively the measured and predicted values of the jth output at the training frequency f_k. This training process is also called backpropagation and it is an ‘on-line’ process whose update equations for \(T_{hi}, W_{hi}, \theta_h\) can be given as follows:

\[T_{hi}^{(k+1)} = T_{hi}^{(k)} - \eta \frac{\partial E^{(k)}}{\partial T_{hi}} + \alpha \left( T_{hi}^{(k)} - T_{hi}^{(k-1)} \right)\]

\[W_{hi}^{(k+1)} = W_{hi}^{(k)} - \eta \frac{\partial E^{(k)}}{\partial W_{hi}} + \alpha \left( W_{hi}^{(k)} - W_{hi}^{(k-1)} \right)\]

\[\theta_h^{(k+1)} = \theta_h^{(k)} - \eta \frac{\partial E^{(k)}}{\partial \theta_h} + \alpha \left( \theta_h^{(k)} - \theta_h^{(k-1)} \right)\]

\[\text{where } \eta \text{ and } \alpha \text{ are learning rate and momentum constants, respectively.}\]
and the similar equations can be written for $\Theta_i$ and $V_i$. In (11.1)-(11.3) $\eta$ and $\alpha$ are positive-valued learning rate and momentum, respectively. Thus we start any set the network parameters and then repeatedly change each parameter by an amount proportional to the terms \[ \frac{\partial E^{(k)}}{\partial T_{bj}} \] according to the eqns. (11.1-11.3) and assume that the training is completed when the error fails to decrease any further. In this case we take the best so far.

Fig. 1 Multi-bias and configuration signal-noise neural network

The sensitivity through the neural network with respect to $T_{bj}, W_{ih}, \Theta_h$ can be given as follows

\[
\frac{\partial E^{(k)}}{\partial T_{bj}} = \delta_{h}^{(1)} f_{j} (1 - f_{j}) g_{h} = - V_{j} (y_{j}^{(k)} - \phi_{j}^{(k)}) f_{j} (1 - f_{j}) g_{h} \quad (12.1) 
\]

\[
\frac{\partial E^{(k)}}{\partial W_{ih}} = \delta_{h}^{(1)} g_{h} \quad (12.2) 
\]

where $\delta_{h}^{(2)}$ and $\delta_{h}^{(3)}$ represent local gradients at individual node in the second and third layer, respectively.

III. PERFORMANCE MEASURE AND RESULTS

To evaluate the quality of the fit to measured data the following error terms are found to be convenient:

\[
E_{S_{ij}} = \frac{1}{n} \sum_{k=1}^{n} \frac{|S_{ij}^{k}_{\text{meas}} - S_{ij}^{k}_{\text{pred}}|}{S_{ij}^{k}_{\text{meas}}} \quad (13) 
\]

\[
E_{N_{i}} = \frac{1}{n} \sum_{i=1}^{n} \frac{|N_{i}^{k}_{\text{meas}} - N_{i}^{k}_{\text{pred}}|}{N_{i}^{k}_{\text{meas}}} \quad (14) 
\]

Where $S_{ij}$ and $N_{i}$ are, respectively the signal and noise parameters, and $n$ is the number of discrete frequencies used. Total average error can be defined as the average of the signal and noise errors:

\[
E_{T} = \frac{1}{4} \sum_{i=1}^{4} E_{signal} + \frac{3}{3} \sum_{i=1}^{3} E_{noise} \quad (15) 
\]

Distribution of errors with frequency for the whole band generalization at multiple bias points for the common collector configuration is given in Fig.3. Simulation results of NE02135 (iter.num.400000) Transistor are given in Fig.4 a-d which shows Distribution of errors with frequency for the whole band generalization at multiple bias points for the common emitter configuration. In addition simulation results of NE219 Transistor are given in Fig.5 a-f which shows variations of S parameters and noise parameters with frequency from 2 - 6 GHz for the $V_{CE}=8V$ and $I_{C}=10, 20$ and $30$ mA at the common emitter configuration which show quite good agreement of the signal parameters over the operation band-width. The graphs include variations of S parameters and noise parameters with frequency from 0.5 - 4 GHz for the $V_{CE}=10V$ and $I_{C}=5, 10, 20$ and $30$ mA at the common emitter configuration.
10, 20 and 30 mA at the common emitter configuration. Finally, variations of S parameters with respect to bias point is given for various constant frequencies. (Fig. 6) Acknowledgement: This work was supported by the Yildiz Technical University Research Fund. Project number: 92-A-04-03-12.

Fig. 2 A perceptron node

Fig. 3 Distribution of errors with frequency for the whole band generalization at multiple bias points for the common collector configuration (NE219)

Fig. 4 Distribution of error for NE02135 transistor at multiple bias points both for signal and noise parameters (if measured noise data exist)
a- $V_{CE}=8 \text{ V}, I_c=10 \text{ mA}$, Common Emitter Configuration (Taught)

Bias Condition: $V_{CE}=8.0 \text{ [Volt]}$, $I_c=10.0 \text{ [mA]}
COMMON EMITTER CONFIGURATION
$E_{II}=0.065763, E_{II}=0.073243$

b- $V_{CE}=8 \text{ V}, I_c=20 \text{ mA}$, Common Emitter Configuration (Taught)

Bias Condition: $V_{CE}=8.0 \text{ [Volt]}$, $I_c=20.0 \text{ [mA]}
COMMON EMITTER CONFIGURATION
$E_{II}=0.065273, E_{II}=0.044730, E_{II}=0.065725$
$E_{II}=0.148137, E_{II}=0.065146$

c- $V_{CE}=8 \text{ V}, I_c=30 \text{ mA}$, Common Emitter Configuration (Interpolated)

Bias Condition: $V_{CE}=8.0 \text{ [Volt]}$, $I_c=30.0 \text{ [mA]}
COMMON EMITTER CONFIGURATION
$E_{II}=0.039886, E_{II}=0.032119, E_{II}=0.042237$
$E_{II}=0.129405, E_{II}=0.058195$

d- $V_{CE}=8 \text{ V}, I_c=10 \text{ mA}$, Common Collector Configuration (Interpolated)

Bias Condition: $V_{CE}=8.0 \text{ [Volt]}$, $I_c=10.0 \text{ [mA]}
COMMON COLLECTOR CONFIG.
$E_{II}=0.07857, E_{II}=0.07930, E_{II}=0.037051$
$E_{II}=0.07582, E_{II}=0.050165$

e- $V_{CE}=8 \text{ V}, I_c=20 \text{ mA}$, Common Collector Configuration (Taught)

Bias Condition: $V_{CE}=8.0 \text{ [Volt]}$, $I_c=20.0 \text{ [mA]}
COMMON COLLECTOR CONFIG.
$E_{II}=0.097500, E_{II}=0.035988, E_{II}=0.049334$
$E_{II}=0.071714, E_{II}=0.041207$

f- $V_{CE}=8 \text{ V}, I_c=30 \text{ mA}$, Common Collector Configuration (taught)

Bias Condition: $V_{CE}=8.0 \text{ [Volt]}$, $I_c=30.0 \text{ [mA]}
COMMON COLLECTOR CONFIG.
$E_{II}=0.036708, E_{II}=0.037123$
$E_{II}=0.066542, E_{II}=0.032068$

Fig. 5 Calculated (------) and measured (- - - -) S parameter shown on Smith chart and polar coordinates for NE219 Transistor at various bias conditions. Error-frequency distribution for $V_{CE}=8 \text{ V}, I_c=20 \text{ mA}$ at the Common Emitter Configuration is also added.
Fig. 6 Variations of S parameters for NE02135 Transistor with respect to bias point (V_{CE}=10\text{V} \ \text{I}_C=2-25 \text{mA}) is given for various frequencies.

REFERENCES

