Extraction of FET Model Noise-Parameters From Measurement

Alfy Riddle

Macallan Consulting
1583 Pinewood Way
Milpitas, CA 95035

ABSTRACT

A rigorous noise-parameter extraction technique for MESFETs and HEMTs is presented. This technique analytically extracts the FET current noise-parameters (P,R, and C) from the measured S- and noise-parameters. This procedure does not require curve fitting, optimization, or simplified noise models. The matrix-based extraction method is derived and shown to be reasonably robust. The sensitivity of this technique to experimental error is also discussed.

INTRODUCTION

Although much work has been done on extraction of FET S-parameter models from measured data, the extraction of noise parameters for an FET model [1-3,10] is less well developed. The matrix-based extraction technique derived in this work is similar to existing S-parameter techniques in that it "peels off" the device parasitics using the appropriate matrix forms and finally yields a set of Y-parameter based matrices which can be directly solved for the model component and noise-parameter values. The set of matrices consists of a component matrix and a noise correlation matrix[4]. The terminal parasitic resistances and inductances are the only components not determined within this procedure. The advantages of this procedure are that it is non-iterative, it does not require curve fitting or optimization, and it uses the most rigorous theoretical model available for FET noise.

This extraction technique determines the P,R, and C coefficients used by van der Ziel and others [5,6]. These coefficients are derived for the intrinsic FET once the parasitic resistances and inductances are removed. The P,R, and C coefficients are frequency independent and form a more rigorous description of the FET noise model than simpler expressions [3,7-9]. This translates to less information being required to describe FET noise over frequency and a more accurate description of R_N and other parameters. The use of P,R, and C coefficients has been limited by their sensitivity, their lack of use in most commercial simulators and the lack of a simple extraction procedure for them.

After a description of the theoretical basis for this work, the algorithm will be applied to two different transistors. The sensitivities of the algorithm to measurement error will also be presented.

THEORY

The noise parameter extraction procedure uses both linear model parameters and noise measurements to simultaneously reduce the noise correlation and circuit element matrices to that of the intrinsic device [4]. The procedure is as follows:

1) convert noise parameters to a Z correlation matrix (C_z)
2) convert the S-parameters to Z parameters
3) de-embed series parasitic elements from Z and C_z.
4) invert the de-embedded Z matrix to get a Y matrix
5) use this Y matrix to derive a C_y from C_z.

Matrix names beginning with "C" are correlation matrices containing the equivalent noise spectral densities of the two ports. The model elements in the final C_y are given as:

$$C_y = 4kT \begin{bmatrix} \dfrac{R(\omega C_{gs})^2}{g_m} & -j\omega C C_{gs}\sqrt{PR} \\ j\omega C C_{gs}\sqrt{PR} & P g_m \end{bmatrix}$$

where R is the gate noise factor, not a resistance. P, R, and C may be extracted from this matrix using the g_m and C_{gs} model parameters found in the component extraction. In practice only the terminal parasitics need be known a priori.

TABLE I

NF_{min}	R_n	Γ_{opt}	S_{11}	S_{12}	S_{21}	S_{22}	P	R	C
0.3	30	0.8∠15	0.99∠-19	0.03∠77	3.47∠164	0.67∠-11	1.4	0.813	-0.019

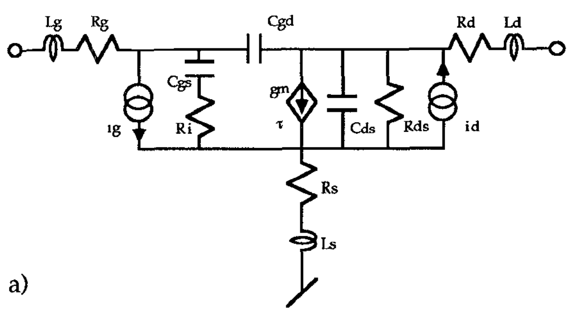
TABLE II

NF_{min}	R_n	Γ_{opt}	S_{11}	S_{12}	S_{21}	S_{22}	P	R	C
0.247	37.4	0.92∠5.6	0.99∠-16	0.019∠82	3.21∠167	0.71∠-3.9	1.41	0.82	0.9

EXAMPLE I

An NEC202 chip HEMT was used as one of the tests of this procedure. The model information, S-parameter data, and noise data from the catalog are shown below in Table I at 2 GHz, 2v, and 10mA. These initially gave reasonable P and R values, but a small negative correlation coefficient.

After checking the catalog data more closely it was found that S-parameters and noise-parameters appeared to be for a different 'typical' devices. By simulating a model based on the NEC data a consistent set of values for all parameters was achieved.



a)

```
ind[{1,2}, 0.1];     (* Lg *)
res[{2,3}, 2.0];     (* Rg *)
res[{4,6}, 3.5];     (* Rs *)
ind[{6,0}, 0.03];    (* Ls *)
res[{5,7}, 4.0];     (* Rd *)
ind[{7,8}, 0.09];    (* Ld *)
fet[{3,4,5}, Ri=4.0, Rds=250.0, Cgs=0.2,
     Cgd=0.016, Cds=0.0072, gm=0.045,
     tau=2.5,{0,P=1.41,R=0.813,C=0.9}];
```

b)

Fig 1. a) FET model, and b) circuit element code.

The model above produced the S- and noise-parameters shown in Table II, which agree with the input data to within 1%, as limited by parameter input precision. Figure 2 shows a comparison of the databook and modeled NEC NFmin.

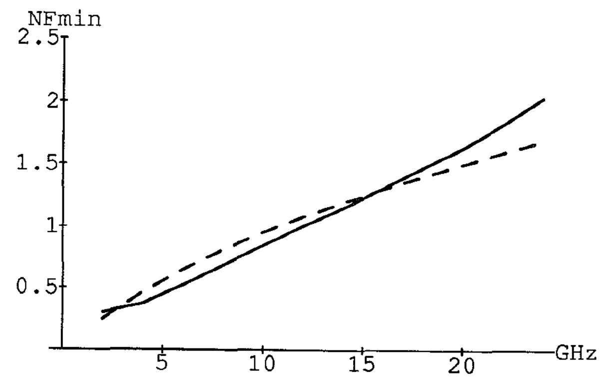


Fig. 2. Databook (solid line) and modeled (dashed line) NFmin for NEC202 HEMT.

A sensitivity study of the extraction method has been performed to help point out potential problems with catalog and measured data. Each parameter is relatively insensitive to 10% variations in NF_{min}, as shown in Figure 3. R_n errors are found to cause variations in P and R, but not C. Γ_{opt} variations or errors cause the greatest change in the C and R parameters, as can be seen in Figure 4. The next most sensitive measurement is the magnitude of S_{11}, as shown in Figure 5. Lastly, the procedure is also sensitive to g_m and $|S_{21}|$.

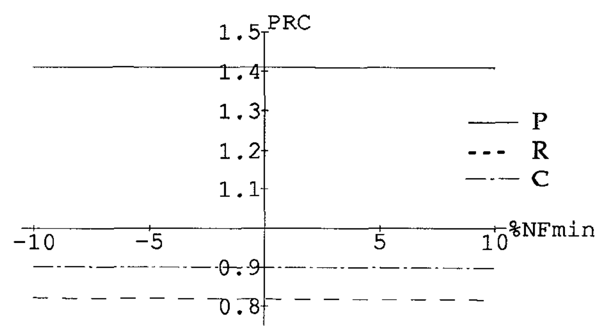


Fig. 3. Variations in extracted P, R, and C with NF_{min} variations.

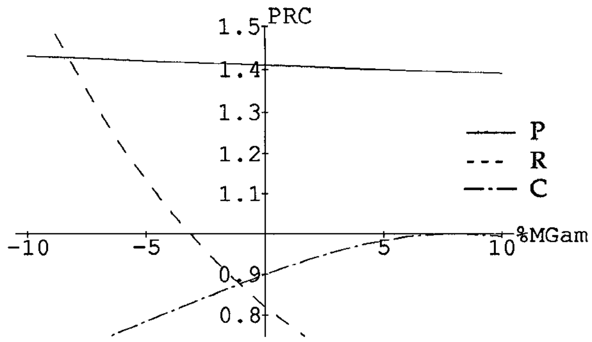


Fig. 4. Sensitivity of extracted P,R, and C to $|\Gamma_{opt}|$ variations.

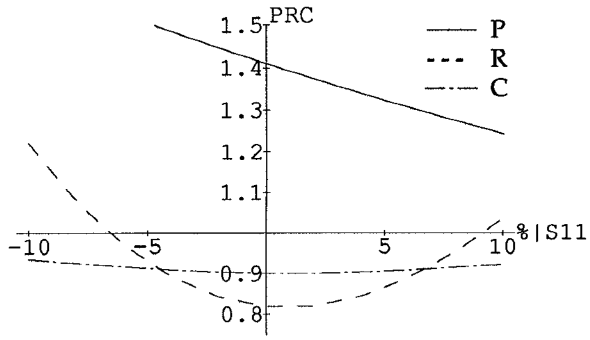


Fig. 5. Sensitivity of extracted P,R, and C to $|S_{11}|$ variations.

It is worth noting that some information is best extracted from noise data. The intrinsic channel resistance, R_i, is very difficult to derive from DC and S-parameter data, yet it has a significant influence on R_n. Since this resistance directly affects R_n an extraction procedure involving S-parameter and noise data simultaneously may give better model results than separate procedures. Simpler methods of noise-parameter extraction often suffer from inaccurate R_n values [9].

EXAMPLE II

A second transistor was measured using a Cascade prober and ATN automated noise measuring system. This device showed less than 1.2db of minimum noise figure up to 18 GHz. Since separate extraction of the resistive and inductive parasitics was not available, values were used which gave a reasonable fit to the S-parameters as shown below in Figure 6.

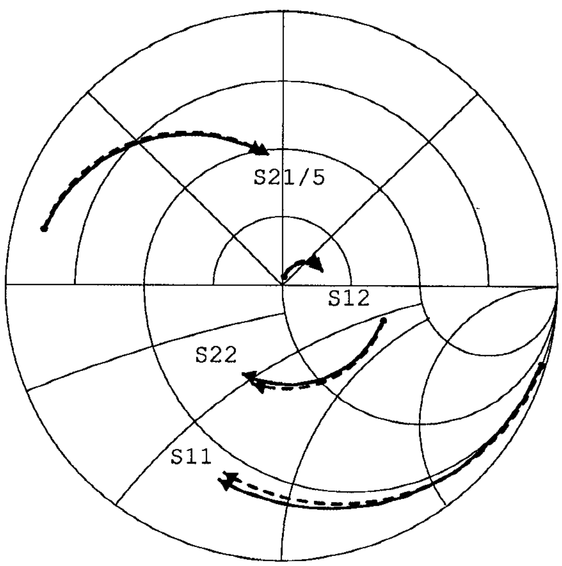


Fig. 6. S-parameters of measured (solid line) and modeled (dashed line) device from 2 to 18 GHz.

Once the parasitic resistances were found the noise extraction program was used to derive the other model component information since the algorithm actually derives both circuit and noise components. The final model used: Rg = 1.0, Rs = 3.5, Rd = 6.0, Ri = 5.0, Rds = 79, Cgs = 0.127 pF, Cgd = 0.036 pF, Cds = 0.075 pF, gm = 94 mSeimens, tau = 1.5 ps, and Lg = 0.025 nH. The noise coefficient extraction algorithm was applied to the measured data at frequency points from 2 to 18 GHz. The resulting P,R, and C parameters should theoretically be constant, but were found to have the following variation:

1) P varied from 1.68 to 1.2,
2) R varied from 2.55 to 0.37, and
3) C varied from 0.38 to 0.6.

This variation could be due to measurement error, improper parasitic resistances and inductances, or incompleteness in the theoretical model. If the computed P, R, and C values are used at each frequency in the model then the measured noise parameters would be found at each frequency. However, this should not be required in theory and the measured NF_{min}, R_N, and Γ_{opt} could just as easily be stored, eliminating the need

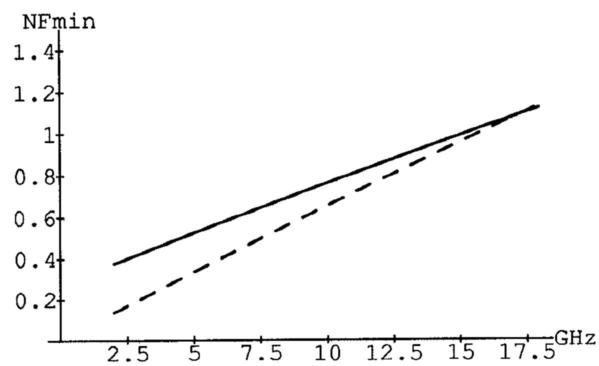


Fig. 7. NF_{min} of measured (solid line), and modeled (dashed line) device from 2 to 18 GHz.

for a more basic device noise description. Certainly the low values of NF_{min} and the possibility of 1/f noise affecting the lowest frequencies make it so the coefficients should be taken from a region of best measurement. The graphs below show a comparison between the measured data and the model using the 14 GHz P, R, and C values. This fit is within measurement error and required no optimization. The noise model parameters were: P = 1.28, R = 0.4, C = 0.6. The computed noise includes the noise in all resistances except for Ri. Each of the plots below uses 17 data points, both measured and computed, at 1 GHz intervals.

The low frequency discrepancy is probably a combination of 1/f noise (note the measured data does not trend toward zero at 0 Hz), and measurement error at low NF. The Γ_{opt} values compared very well in magnitude and angle, although at the lowest frequencies the model predicted a higher magnitude of Γ_{opt}, 0.9 as opposed to 0.84. This is easily explained by tuners having difficulty at higher VSWRs. The model contains a natural change in R_N with frequency, the change is small compared to the measured data unless the value of P is also allowed to vary. This may indicate measurement error since the NEC device, and the device in [10] each have large R_N variations when modeled with fixed P values.

CONCLUSIONS

The goal of this work has been to extract the coefficients of a rigorous FET noise model from measurements without curve-fitting or optimization. This is important since it establishes the accuracy of the basic model and potentially minimizes the data required to describe FET noise and minimizes the time to extract a model. A matrix based method for doing this has been described and verified. Other methods require curve-fitting to NF_{min} and approximate formulas for R_N and Γ_{opt}. These methods can easily approximate NF_{min} because it is so close to a straight line, but often fail when trying to obtain accurate values for R_N or Γ_{opt}.

This algorithm presented is straightforward and easily implemented on a computer. Because of the similarities between MESFETs and HEMTs the procedure works equally well for both. There is relatively little sensitivity of any of the coefficients to the minimum noise figure. It is the combination of these elements that affects the noise figure, and in particular a subtraction of two nearly equal terms that allows the individual terms to change very little while the noise figure changes substantially [7]. Dominant sensitivities are due to the magnitude of Γ_{opt} and $|S11|$.

A few rules of thumb regarding the coefficients may be useful. The R coefficient mainly affects Γ_{opt}. The P coefficient affects both R_N and NF_{min}. Large changes in R_N may require P to change, though a theoretical explanation for this is not known. C scales NF_{min}.

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