# Polynomial-Based Extraction Procedure for Determination of HEMT Noise Wave Temperatures

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*Abstract* – **The noise wave model defines relationships between the noise wave parameters and the noise parameters. As the noise wave model is related to device intrinsic circuit and available measured transistor noise parameters are related to the whole device, the noise wave parameters are usually extracted using time-consuming optimization procedures in circuit simulators. In this paper, a new, faster and more efficient extraction procedure based on using polynomial functions is presented. The detailed validation of the proposed procedure is done by comparison of the transistor noise parameters of the entire circuit, obtained by using the noise wave parameters extracted by the proposed approach, with the measured transistor noise parameters.**

*Keywords* –**HEMT, noise parameters, noise wave model, noise wave parameters, polynomials.**

## I. INTRODUCTION

The need for precise noise modeling of microwave transistors (MESFETs/HEMTs) that are used in modern microwave communication systems, has led to development of different transistor noise models [1-10]. These models enable implementation of transistors within microwave circuit simulators, which results in the efficient noise analysis. The main classification of transistor noise models is into physical and empirical noise models. Most microwave circuit designers use the empirical noise models since the parameters related to device physical characteristics are often unavailable. The parameters of the empirical noise models are usually extracted from the measured transistor noise parameters ($F_{min}$ – minimum noise figure, $\Gamma_{opt}$ – optimum source reflection coefficient and $r_n$ – normalized noise resistance).

In recent years, the noise wave model treating the noise in terms of waves has appeared as a very appropriate noise model at the microwave frequencies [2], [7-9], [11-19]. The wave representation of noise provides a suitable alternative to the most commonly used representations of noise generated in two-port network based on the equivalent voltage and/or current sources [6]. The noise wave parameters are the noise wave temperatures and it is shown that these temperatures are frequency dependent [14]. The extraction of the frequency dependent noise wave temperatures is usually done using the optimization procedures in circuit simulators. However, the fact that the optimization procedures are time-consuming makes them relatively inefficient extraction tool.

In this paper, a new, faster and more efficient extraction procedure based on using polynomial functions is proposed. In addition to saving time, the proposed extraction procedure also enables a very accurate transistor noise modeling using the noise wave model.

The paper is organized as follows: after Introduction, Section II contains a short description of the noise wave model. Polynomial-based extraction procedure is presented in Section III. Section IV contains the most illustrative numerical results and obtained observations. Concluding remarks are given in Section V.

## II. NOISE WAVE MODEL OF MICROWAVE FETS

Noise in linear two-port networks can be characterized in many different ways. In the noise wave representation, a noisy two-port network is described by using a noiseless linear equivalent circuit and the waves that emanate from its ports [2].

It is very convenient to use the noise wave temperatures as empirical model parameters, as in that way the noise performance of any two-port network can be completely characterized by the two real temperatures, $T_a$ and $T_b$, and the complex correlation temperature, $T_c = |T_c| e^{j\omega\tau_c}$. These temperatures can be expressed in terms of the noise parameters of transistor intrinsic circuit - minimum noise figure, $F_{mini}$, optimum source reflection coefficient, $\Gamma_{opti} = |\Gamma_{opti}| e^{j\varphi_{opti}}$, and noise resistance, $R_{ni}$, as [2]:

$$T_a = T_0(F_{mini} - 1) + \frac{4R_{ni}T_0|\Gamma_{opti}|^2}{Z_0|1+\Gamma_{opti}|^2}, \quad (1)$$

$$T_b = \frac{4R_{ni}T_0}{Z_0|1+\Gamma_{opti}|^2} - T_0(F_{mini} - 1), \quad (2)$$

$$T_c = \frac{4R_{ni}T_0\Gamma_{opti}}{Z_0|1+\Gamma_{opti}|^2}, \quad (3)$$

where $Z_0$ - the normalization impedance (50$\Omega$) and $T_0$ - the standard reference temperature (290K).

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## III. PROPOSED POLYNOMIAL-BASED EXTRACTION PROCEDURE

As already mentioned, the optimization procedures in circuit simulators that are usually used for extraction of the noise wave temperatures are time-consuming. Instead, the extraction of the noise wave temperatures can be done by using efficient polynomial-based procedure illustrated in Fig. 1, which is detailed as follows:

1. Design the small-signal equivalent circuit schematic of the considered transistor within the standard circuit simulator and implement the noise wave model expressions,
2. Generate *n* random samples of the noise parameters of transistor intrinsic circuit ($F_{mini}$, $R_{ni}$, $|\Gamma_{opti}|$, and $\varphi_{opti}$),
3. For each of *n* samples of the noise parameters generated in a previous step, calculate the noise wave temperatures ($T_a$, $T_b$, $|T_c|$, and $\tau_c$) using Eqs. (1-3),
4. Assign the calculated noise wave temperatures to the noise wave model implemented within the standard circuit simulator in step 1,
5. Simulate the noise parameters of entire transistor ($F_{min}$, $R_n$, $|\Gamma_{opt}|$, and $\varphi_{opt}$) at the considered frequency range, ambient temperature and operating conditions,
6. Apply the Eqs. (1-3) to the noise parameters of entire circuit obtained by simulations, and calculate the fictive noise wave temperatures ($T_{af}$, $T_{bf}$, $|T_{cf}|$, and $\tau_{cf}$) referring to the whole circuit,
7. Express the correlations between the noise wave temperatures and the fictive noise wave temperatures for the considered frequency range by using first degree ($m$ = 1) polynomials,
8. Based on the measured noise parameters of the considered transistor, calculate the fictive noise wave temperatures ($T_{af}$, $T_{bf}$, $|T_{cf}|$, and $\tau_{cf}$) using Eqs. (1-3),
9. Use the calculated fictive noise wave temperatures and obtained correlations expressed by polynomials to determine the noise wave temperatures ($T_a$, $T_b$, $|T_c|$, and $\tau_c$),
10. In order to validate the proposed extraction procedure, assign the extracted noise wave temperatures to the noise wave model implemented within the standard circuit simulator in step 1,
11. Simulate the noise parameters of entire transistor ($F_{min}$, $R_n$, $|\Gamma_{opt}|$, and $\varphi_{opt}$) at the same frequency range, ambient temperature and operating conditions as in step 5,
12. Compare the obtained noise parameters with the measured ones,
13. If the obtained results do not have satisfactory accuracy, increase a polynomial degree ($m$) by 1, and repeat steps from 7-12. Otherwise, use the noise wave temperatures extracted in step 9.

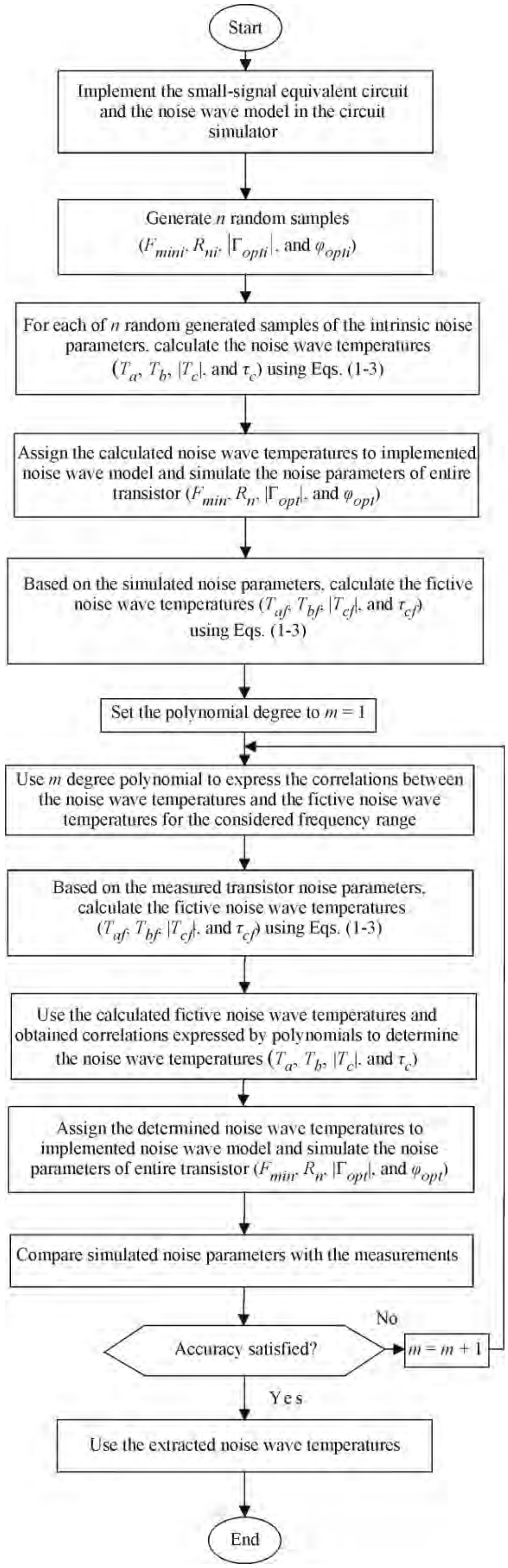



Fig. 1. Proposed polynomial-based extraction procedure flowchart.

## IV. Numerical Results

The proposed polynomial-based extraction procedure was applied to a packaged HEMT, type NE20283A by NEC, and some of the obtained results are presented in this paper. All simulations were performed using microwave circuit simulator ADS (Advanced Design System) [20]. Measured *S* and noise parameters have been available in the frequency range 6-18 GHz over the temperature range 233-333 K, step 20 K [21].

The equivalent circuit of a packaged HEMT used in this research is shown in Fig. 2 [21]. The intrinsic circuit is denoted by the dashed line, and it is common to the most of microwave FET models. The remaining elements embedded in the extrinsic circuit represent parasitic effects and the package.

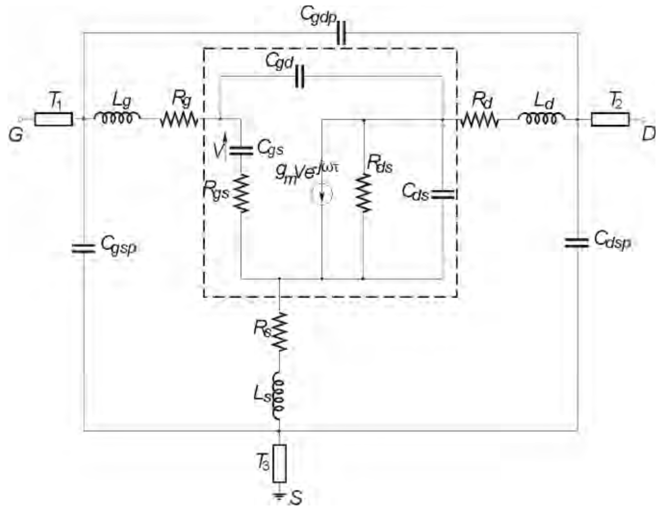



Fig. 2. Equivalent circuit of HEMT in packaged form.

As can be seen in Fig. 2, there are 19 equivalent circuit elements (*ECPs*). The values of small-signal *ECPs* of the considered transistor were taken from [21].

First, the values of the noise parameters of transistor intrinsic circuit were generated randomly. Then, the noise wave temperatures determined from these random generated intrinsic noise parameters were used to obtain the fictive noise wave temperatures within ADS [20] circuit simulator. In this case, for the considered frequency range, the correlations between the noise wave temperatures and the fictive noise wave temperatures were expressed with high accuracy by the first degree polynomials:

$$T_a[\mathrm{K}] = x_a + y_a T_{af}[K] + z_a f[\mathrm{GHz}], \qquad (4)$$

$$T_b[\mathrm{K}] = x_b + y_b T_{bf}[K] + z_b f[\mathrm{GHz}], \qquad (5)$$

$$|T_c|[\mathrm{K}] = x_c + y_c |T_{cf}|[K] + z_c f[\mathrm{GHz}], \qquad (6)$$

$$\tau_c[\mathrm{ps}] = x_d + y_d \tau_{cf}[\mathrm{ps}] + z_d f[\mathrm{GHz}], \qquad (7)$$

where $x_{a\text{-}d}$, $y_{a\text{-}d}$ and $z_{a\text{-}d}$, are the polynomial coefficients given in Table I for different ambient temperatures, and $f$ is the frequency. The frequency is included in Eqs. (4-7) because the noise parameters of transistor extrinsic circuit are frequency dependent. Also, all the units of variables in Eqs. (4-7) were marked within square brackets.

Table I
Polynomial coefficients for different ambient temperatures

| | | 233 K | 253 K | 273 K | 293K | 313 K | 333 K |
|---|---|---|---|---|---|---|---|
| $T_a$ | $x_a$ | -82.09 | -99.12 | -109.3 | -82.07 | -48.95 | -54.6 |
| | $y_a$ | 1.507 | 1.584 | 1.567 | 1.257 | 0.97 | 0.976 |
| | $z_a$ | 4.92 | 4.973 | 4.836 | 5.9 | 7.662 | 8.364 |
| $T_b$ | $x_b$ | -98.4 | -77.26 | -149.1 | -164.2 | -100.1 | -110.7 |
| | $y_b$ | 1.54 | 1.218 | 1.702 | 1.72 | 1.233 | 1.244 |
| | $z_b$ | 7.226 | 8.385 | 9.251 | 9.852 | 10.48 | 11.63 |
| $\|T_c\|$ | $x_c$ | -70.38 | -67.85 | -107.3 | -171.4 | -102 | -105.1 |
| | $y_c$ | 1.178 | 1.055 | 1.248 | 1.618 | 1.136 | 1.096 |
| | $z_c$ | 8.696 | 9.901 | 11.7 | 13.62 | 13.47 | 14.85 |
| $\tau_c$ | $x_d$ | 25.3 | 24.23 | 23.49 | 23.37 | 24.24 | 24.75 |
| | $y_d$ | -0.098 | -0.065 | -0.046 | -0.044 | -0.046 | -0.058 |
| | $z_d$ | -0.332 | -0.345 | -0.348 | -0.346 | -0.372 | -0.372 |

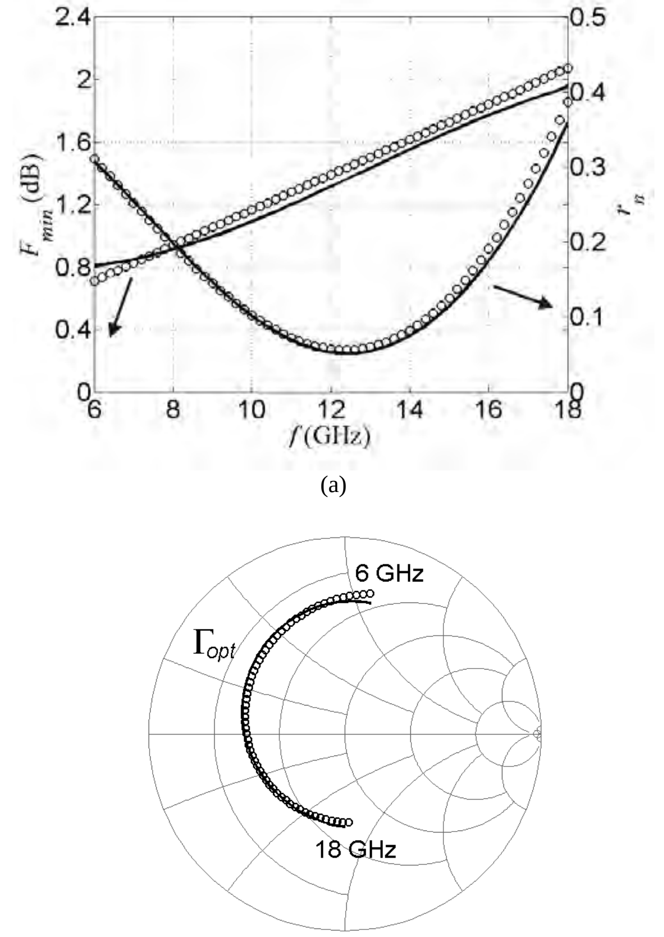
The polynomial coefficients from Table I and the fictive noise wave temperatures calculated from the measured transistor noise parameters were used for determination of the noise wave temperatures. In order to validate the proposed polynomial-based extraction procedure, the determined noise wave temperatures were assigned to the noise wave model implemented within ADS [20], and the noise parameters of entire transistor circuit were simulated. The simulated noise parameters were then compared with the corresponding measured data.

As an illustration, Fig. 3 presents the simulated $F_{min}$, $r_n$, and $\Gamma_{opt}$ and the corresponding measured data. The results shown in Fig. 3 were obtained for the ambient temperature of 313 K in the frequency range from 6 to 18 GHz. It can be seen that the simulated values of noise parameters are very close to the measured ones, confirming the accuracy of the proposed extraction procedure. The results for the other available temperatures show the same level of the noise modeling accuracy.

## V. Conclusion

Because the noise wave temperatures are frequency dependent, the optimization procedures in circuit simulators usually used for their extraction become time-consuming. For this reason, a new efficient extraction procedure was proposed in this paper. The presented procedure is based on the polynomial correlations between the noise wave temperatures and the fictive noise wave temperatures of entire transistor.

The proposed procedure was applied to a specific HEMT device in a packaged form. Extraction of the noise wave temperatures was carried out based on the polynomial expressed correlations between them and the fictive noise wave temperatures calculated from the available measured transistor noise parameters. Based on the obtained noise wave temperatures, the corresponding noise parameters of entire transistor circuit were calculated in the circuit simulator. A good agreement between simulated and measured transistor noise parameters in a wide range of ambient temperatures proves validity of the proposed procedure.




(a)

(b)

Fig. 3. Measured (symbols) and simulated (lines) values of: (a) $F_{min}$ and $r_n$, (b) $\Gamma_{opt}$ ,depending on the frequency at 313K.

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