temperatures - two real temperatures, T_a and T_b, and one 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, $F_{min,i}$, optimum source reflection coefficient, $\Gamma_{opt,i} = |\Gamma_{opt,i}| e^{j\varphi_{opt,i}}$, and noise resistance, $R_{n,i}$, as [2]:

$$T_a = T_0 (F_{min,i} - 1) + \frac{4 R_{n,i} T_0 |\Gamma_{opt,i}|^2}{Z_0 |1 + \Gamma_{opt,i}|^2}, \tag{1}$$

$$T_b = \frac{4 R_{n,i} T_0}{Z_0 |1 + \Gamma_{opt,i}|^2} - T_0 (F_{min,i} - 1), \tag{2}$$

$$T_c = \frac{4 R_{n,i} T_0 \Gamma_{opt,i}}{Z_0 |1 + \Gamma_{opt,i}|^2}, \tag{3}$$

where Z_0 is the normalization impedance (50 Ω) and T_0 is the standard reference temperature (290 K).

III. The Proposed ANN Approach for Microwave FET Noise Wave Temperature Extraction

As already mentioned, since the noise wave model is related to the transistor intrinsic circuit, the noise wave temperatures are in relationships with the noise parameters of transistor intrinsic circuit, Eqs. (1-3) [2]. However, because the noise parameters of transistor intrinsic circuit are not directly measurable, direct analytical determination of these temperatures is not possible. Instead, the noise parameters of transistor intrinsic circuit can be replaced by the fully measurable transistor noise parameters in Eqs. (1-3), which leads to determination of the fictive noise wave temperatures, T_{af}, T_{bf}, $|T_{cf}|$, and τ_{cf}. Compared to the noise wave temperatures that are related to the transistor intrinsic circuit, the fictive noise wave temperatures are related to the entire transistor. Although the fictive noise wave temperatures are irrelevant to the process of the transistor noise modeling, they can be very useful for the extraction of the noise wave temperatures [21]. Namely, as it has already been shown earlier, there is a strong correlation between the noise wave temperatures and the fictive noise wave temperatures [21]. Exactly this fact is used for development of a novel approach for efficient extraction of the noise wave temperatures, which enables avoiding time-consuming optimization procedures in circuit simulators.

The developed approach for extraction of the noise wave temperatures is based on ANN model presented in Fig. 1. The presented ANN is trained to determine the noise wave temperatures, T_a, T_b, $|T_c|$, and τ_c, from the fictive noise wave temperatures, T_{af}, T_{bf}, $|T_{cf}|$, and τ_{cf}, frequency, f, and ambient temperature, T. The presented ANN is based on a standard multilayer perceptron (MLP) structure [23] that consists of basic processing elements (neurons) grouped into layers: an input layer, an output layer, as well as one/several hidden layers. In the case of MLP structure, each neuron is connected to all neurons from the adjacent layers, whereas there are no connections among neurons belonging to the same layer. Each neuron is characterized by a transfer function and each connection is weighted. The ANN learns relationship among sets of input–output data (training sets) by adjusting network connection weights and thresholds of activation functions. There are different algorithms for training of ANNs. The most frequently used are the backpropagation algorithm and its modifications with higher convergence order, as the Levenberg-Marquard algorithm [23].

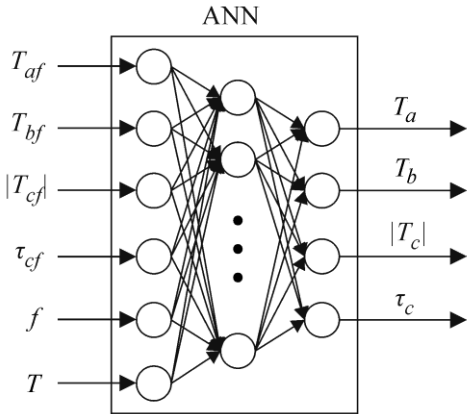


Fig. 1. The proposed ANN model for extraction of the noise wave temperatures.

The procedure of ANN training and validation is illustrated in the flowchart given in Fig. 2 and can be described 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 R and L ($L \geq 0.1R$) random samples of $F_{min,i}$, $R_{n,i}$, $|\Gamma_{opt,i}|$, $\varphi_{opt,i}$, f and T,
3. For each of R and L samples of $F_{min,i}$, $R_{n,i}$, $|\Gamma_{opt,i}|$, and $\varphi_{opt,i}$, calculate T_a, T_b, $|T_c|$, and τ_c, using Eqs. (1-3),
4. For R and L different combinations of calculated values of T_a, T_b, $|T_c|$, and τ_c, and randomly sampled values of f and T, simulate the noise parameters of entire transistor, F_{min}, R_n, $|\Gamma_{opt}|$, and φ_{opt}, by using the noise wave model implemented within the standard circuit simulator in step 1,
5. Apply the Eqs. (1-3) to the simulated values of F_{min}, R_n, $|\Gamma_{opt}|$, and φ_{opt}, and calculate T_{af}, T_{bf}, $|T_{cf}|$, and τ_{cf},
6. Build the training set (R samples) and validation test set (L samples), where the inputs are T_{af}, T_{bf}, $|T_{cf}|$, τ_{cf}, f and T, and outputs are T_a, T_b, $|T_c|$, and τ_c,
7. Train a certain number of ANNs with one hidden layer and different number of hidden neurons,
8. Validate ANNs by comparing ANN response with the reference values not used for the network training (validation test set with L samples),

9. If the test results do not have satisfactory accuracy, increase *R* and repeat steps 2-8. Otherwise, proceed to the next step,
10. Choose ANN showing the best statistics. That network is further used for the extraction of the noise wave temperatures.

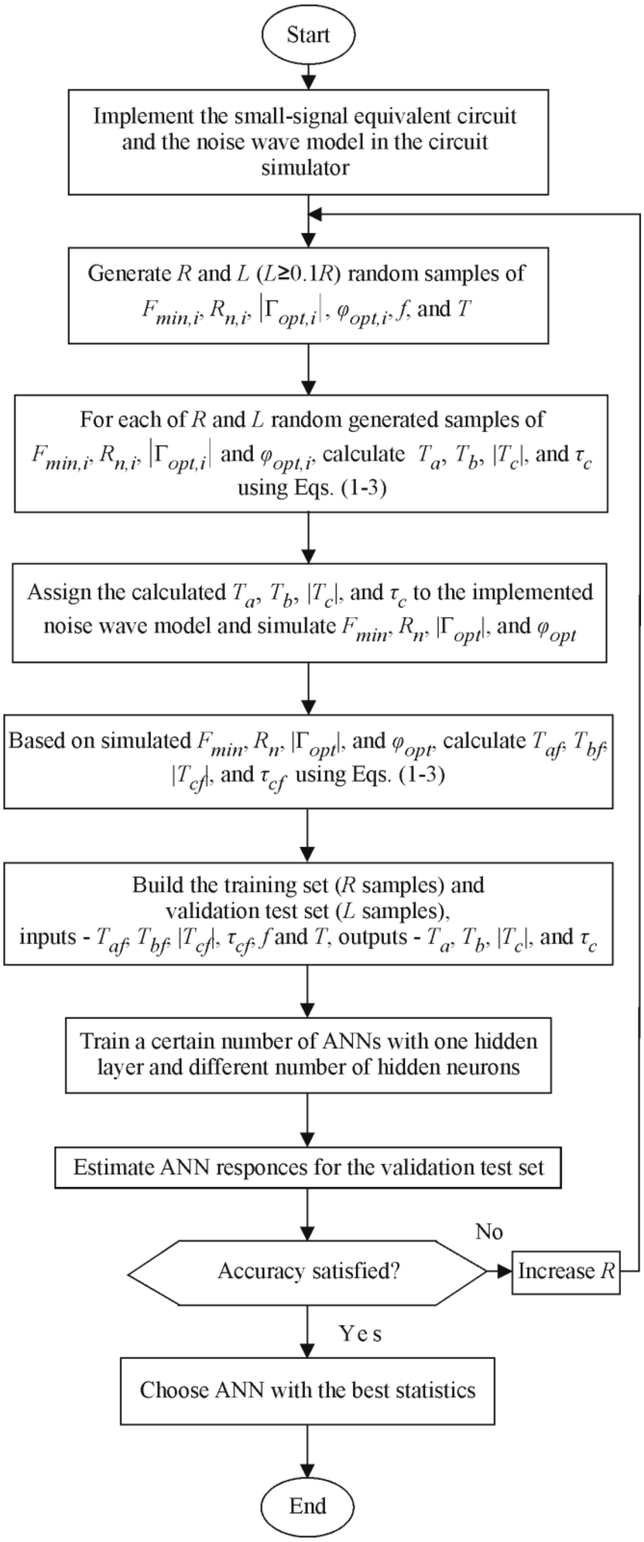


Fig. 2. Flowchart illustrating the training procedure of ANNs that are used for extraction of the noise wave temperatures.

IV. Numerical Results and Discussion

In order to validate the presented ANN approach for extraction of the noise wave temperatures, it was applied to a packaged HEMT based on AlGaAs/GaAs heterojunction, type NE20283A by NEC. In the case of the considered transistor, the *S* parameters were measured by using a vector network analyzer, whereas the noise parameters were obtained from the noise figure measured in input matched conditions, F50 [30]. They were available in the frequency range 6-18 GHz over the temperature range 233-333 K, 20 K step.

The equivalent circuit of a packaged HEMT, which was used for validation of the presented ANN extraction approach, is shown in Fig. 3 [30]. It consists of intrinsic and extrinsic parts. The intrinsic circuit is common to the most of microwave FET models, and it is denoted by the dashed line. Parasitic effects and the package are represented by the remaining extrinsic elements embedded in the circuit.

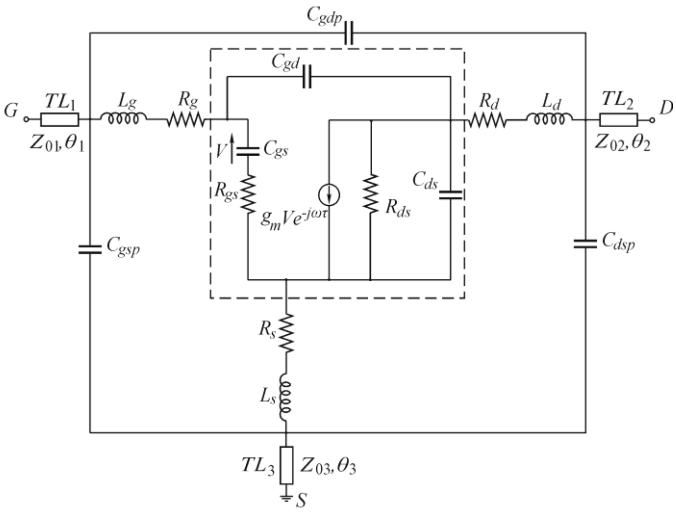


Fig. 3. Equivalent circuit of HEMT in packaged form.

As can be seen in Fig. 3, there are 19 equivalent circuit elements. The values of small-signal equivalent circuit elements of the considered transistor were taken from [30].

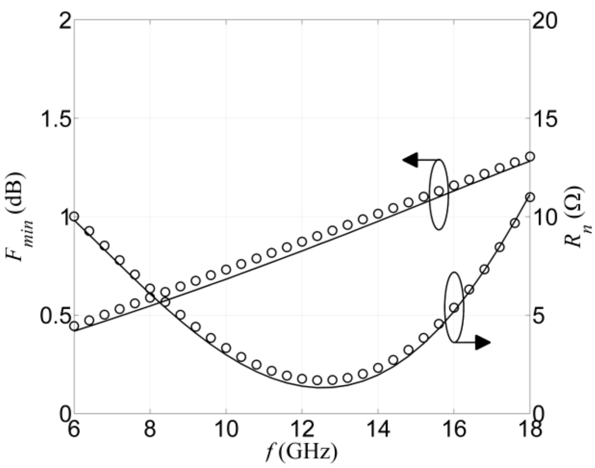
First, the values of the noise parameters of transistor intrinsic circuit were generated randomly. Then, the noise wave temperatures determined from these random generated noise parameters of transistor intrinsic circuit were used to obtain the fictive noise wave temperatures within ADS [31] circuit simulator. After that, the appropriate training and validation test sets with a certain number of samples were built. By using the built training set and the Levenberg-Marquard algorithm [23], several ANNs with one hidden layer and different number of hidden neurons were trained within MATLAB [32] software environment. To estimate the accuracy of the ANN learning and generalization, the trained ANNs were tested on the built training and validation test sets, respectively, by using the following metrics: average test error (ATE), worst case error (WCE), and Pearson product-moment correlation coefficient (*r*) [23]. It should be mentioned that the number of samples within the training set was gradually increased and the process of ANN training was repeated until the network with the best performance was obtained. Among the trained ANNs, ANN with the highest accuracy has one hidden layer, with five neurons. This ANN was trained with the training set contained 329 samples, whereas the validation test set contained 37 samples. The test statistics on training and validation test set for the chosen ANN is given in Table I.

TABLE I
TEST STATISTICS FOR THE CHOSEN ANN

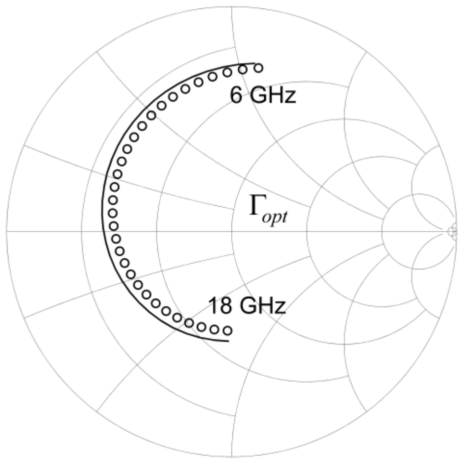
	ATE (%)	WCE (%)	r
Training set			
T_a	0.1238	0.5509	0.999970149
T_b	0.1021	0.4989	0.999981464
$\|T_c\|$	0.0904	0.4473	0.999985470
τ_c	0.1618	0.8713	0.999968505
Validation test set			
T_a	0.1595	0.4529	0.999968256
T_b	0.1197	0.5843	0.999978037
$\|T_c\|$	0.1141	0.5185	0.999981384
τ_c	0.1697	0.7527	0.999972099

The proposed ANN was used for determination of the noise wave temperatures in the whole temperature and frequency range. In order to validate the presented ANN based extraction approach, the determined noise wave temperatures were assigned to the noise wave model implemented within ADS [31], and the transistor noise parameters were simulated. The simulated noise parameters were compared with the corresponding measured data.

As an illustration, Figs. 4 and 5 present the simulated F_{min}, R_n, and Γ_{opt} and the corresponding measured data. The results shown in Figs. 4 and 5 were obtained for the ambient temperatures of 233 K and 253 K, respectively, 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 approach.

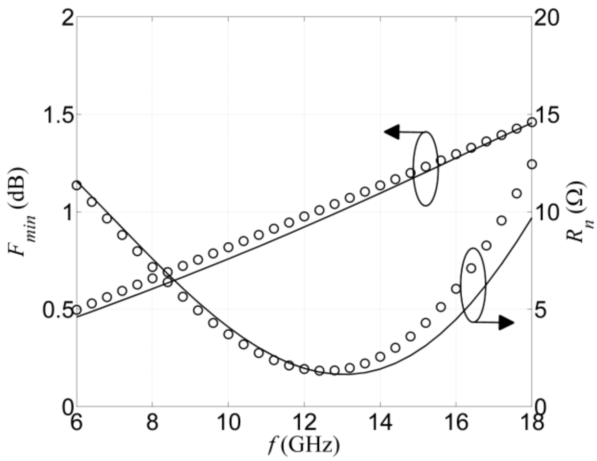


(a)

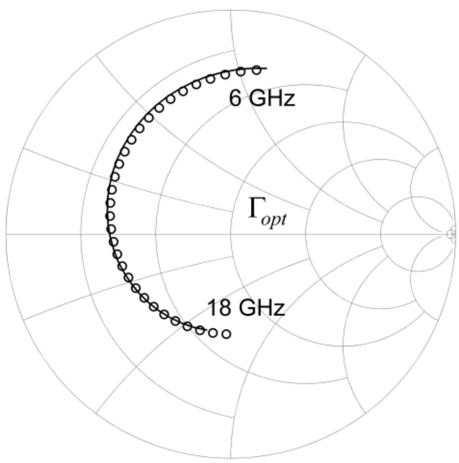


(b)

Fig. 4. Measured (symbols) and simulated (lines) values of: (a) F_{min} and R_n, (b) Γ_{opt} ,depending on the frequency at 233 K.



(a)



(b)

Fig. 5. Measured (symbols) and simulated (lines) values of: (a) F_{min} and R_n, (b) Γ_{opt} ,depending on the frequency at 253 K.

V. Conclusion

The noise wave temperatures are extracted based on the measured transistor noise parameters usually using optimization procedures within microwave circuit simulators. As the noise wave temperatures are frequency dependent parameters, the optimization procedures used for their extraction are time-consuming. In this paper, the more efficient extraction approach based on ANNs is presented. Namely, ANN is trained to determine the noise wave temperatures based on the fictive noise wave temperatures, frequency and ambient temperature.

With the aim to validate the proposed extraction approach, it was applied to a specific packaged HEMT over wide temperature range. The corresponding noise parameters of entire transistor circuit were simulated in the circuit simulator based on the obtained noise wave temperatures. A good agreement between the simulated and the measured transistor noise parameters proves validity of the proposed extraction approach.

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