In-Situ Input Impedance Determination of Low Noise Amplifiers in Radiometric Applications

Dominik Kraft(1), Fabian Ströder(1)(2), Daniel Erni(2), Klaus Thelen(1)

(1) Institute of Measuring and Sensor Technology, Ruhr West University of Applied Science, Mülheim an der Ruhr, Germany
(2) General and Theoretical Electrical Engineering (ATE), University of Duisburg-Essen, and Center for Nanointegration Duisburg-Essen (CENIDE), D-47048 Duisburg, Germany

***Abstract*—With radiometric thermometry the temperature of weakly conductive objects placed in closed cavities can be determined by measuring the emitted Planck radiation captured by an antenna. In order to calibrate the system, the complex electrical coupling coefficient between object and a low noise amplifier (LNA) must be known. This study introduces a mathematical extension to a former presented self-calibrating radiometry method. The previous approach assumed a constant 50 Ω input impedance for the LNA used. To address variations in the LNA's input impedance, an in-situ method is introduced to determine the complex reflection coefficient of the amplifier. Therefore, a three-impedance calibration technique, utilizing short-circuit, open-circuit, and capacitive loads, is developed. By resolving resulting circular equations in the complex plane of the LNA's reflection coefficient, the impedance of the LNA can be determined, thereby enabling the functionality of the self-calibrating radiometer design.**

Keywords—amplifiers, low noise amplifiers, calibration, electromagnetic reflection, microwave radiometry, reflection coefficient, temperature measurement, wide-band radiometer

I. Introduction

An extension of the approach published in [1] for non-invasive temperature measurement of weakly conductive objects in closed cavities, based on thermal radiation and Planck's law [2], is described. The method employs various combinations of reference impedances, capacitances, noise sources and ground connections, to achieve self-calibration and to determine parameters such as system gain, the reflection coefficient of the object in the cavity, and its impedance. These parameters are essential for calculating the object's absolute temperature. A major advantage of this method is its use of a directional coupler (DC) instead of a circulator, which enables a wide-band operation and requires only simple measurement electronics, distinguishing it from conventional radiometer applications [3, 4].

However, the design assumes a low noise amplifier (LNA) with an ideal 50 Ω input impedance across the measurement bandwidth. This impedance varies with frequency, resulting in a voltage divider ratio between the object and the LNA that changes according to the LNA's input impedance. Since the object temperature is proportional to its emitted noise power, accurate determination of the voltage divider ratio is essential to calculate the emitted thermal noise power from the noise power measured at the LNA output.

Here, a mathematical approach for in-situ determination of the reflection coefficient and, thus, the input impedance of the LNA is incorporated into the concept in [1]. This approach accounts for additional signal reflections at the LNA input. Initially, the signal reflections are mathematically modelled. The mathematical extension for in-situ determination of the LNA input impedance is described subsequently.

II. Determination of LNA Input Impedance

The frequency-dependent input impedance of the LNA and the resulting signal reflections at its input are incorporated into the design of a self-calibrating radiometer [1]. A method for calculating the LNA's reflection coefficient based on three known impedances connected to the LNA input is presented. Therefore, the concept is expanded to include three additional loads at ports 3, 4 and 5 of switch C as shown in Fig. 1. Further details regarding the structure are available in [1].

To determine the LNA's reflection coefficient, two noise sources (switch B) are used. Their noise power levels simulate both temperatures $T_{1,2}$. According to the equation for thermal noise and taking into account the attenuation factor β of the coupled path of the DC, initial waves $a^0_{1,2}$ (1) propagate from the noise sources into the reference plane (blue line) [2].

$$a^0_{1,2} = \beta \cdot \sqrt{T_{1,2} \cdot k_\mathrm{B} \cdot \Delta f} \tag{1}$$

Here, k_B denotes the Boltzmann constant and Δf is the measurement bandwidth.

In the reference plane the reflection coefficients are $\underline{r}_\mathrm{x}$ towards the object dependent antenna impedance $\underline{Z}_x$ and $\underline{r}_\mathrm{LNA}$ towards the LNA. Due to impedance mismatch between the LNA input and $\underline{Z}_\mathrm{x}$, the LNA receives the two superimposed waves $b^\mathrm{tot}_{1,2}$ consisting of the initial reflection of $a^0_{1,2}$ from $\underline{Z}_\mathrm{x}$ and an infinite series of subsequent reflections between $\underline{Z}_\mathrm{x}$ and the LNA (2).

$$b^\mathrm{tot}_{1,2} = a^0_{1,2} \cdot \left|\sum_{\mathrm{n}=1}^{\infty} \underline{r}_\mathrm{x}^\mathrm{n} \cdot \underline{r}_\mathrm{LNA}^\mathrm{n-1}\right| = a^0_{1,2} \cdot \left|\frac{\underline{r}_\mathrm{x}}{1-\underline{r}_\mathrm{x} \cdot \underline{r}_\mathrm{LNA}}\right| \tag{2}$$

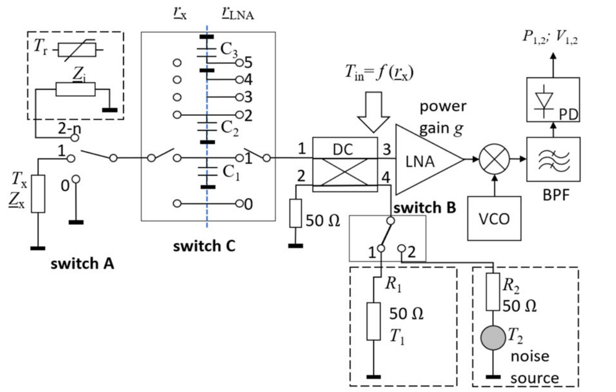


Fig. 1. Schematic of the self-calibrating radiometer

Subtracting the uncorrelated voltages $V_{1,2}$ measured at the LNA output yields (3), where V_x is an unknown parameter with units of volts, that contains the LNA´s gain and the waves from (1). In both measurements the same source impedance applies to the LNA input, so the LNA's intrinsic noise remains constant and its influence is eliminated in (3). The same holds for the noise of the impedance to the left of the reference plane.

$$\Delta V_\mathrm{out} = \sqrt{{V_2}^2 - {V_1}^2} = V_\mathrm{x} \cdot \left|\frac{\underline{r}_\mathrm{x}}{1-\underline{r}_\mathrm{x}\underline{r}_\mathrm{LNA}}\right| \tag{3}$$

To determine the reflection coefficient $\underline{r}_\mathrm{LNA}$, three known calibration impedances are successively connected to the reference plane at switch C, thereby defining $\underline{r}_\mathrm{x}$ in (3). These impedances are selected to maximise reflection of the noise signal, enables improvements in measuring the differential voltage ΔV_out. The first impedance applied at switch C port 3 is an open circuit ($\underline{r}_\mathrm{x} = 1$). After rearrangement of (3), the measured differential voltage ($\Delta V_\mathrm{out} = V_\mathrm{o}$) yields a circular equation in the complex plane of $\underline{r}_\mathrm{LNA}$ with the radius R_o (4).

$$R_\mathrm{o}^2 = \left(\frac{V_\mathrm{x}}{V_\mathrm{o}}\right)^2 = \left|1 - \underline{r}_\mathrm{LNA}\right|^2 = \left(1 - \mathrm{Re}\{\underline{r}_\mathrm{LNA}\}\right)^2 + \mathrm{Im}\{\underline{r}_\mathrm{LNA}\}^2 \tag{4}$$

When a short circuit ($\underline{r}_\mathrm{x} = -1$) is applied at switch C port 4, the measured differential voltage ($\Delta V_\mathrm{out} = V_\mathrm{s}$) provides a second circular equation with the radius R_s (5).

$$R_\mathrm{s}^2 = \left(\frac{V_\mathrm{x}}{V_\mathrm{s}}\right)^2 = \left|1 + \underline{r}_\mathrm{LNA}\right|^2 = \left(1 + \mathrm{Re}\{\underline{r}_\mathrm{LNA}\}\right)^2 + \mathrm{Im}\{\underline{r}_\mathrm{LNA}\}^2 \tag{5}$$

The intersection points of these two circles yield two potential solutions for $\underline{r}_\mathrm{LNA}$. However, since V_x remains unknown, the exact radii of the circles are undefined, leaving the true reflection coefficient undetermined. To resolve this ambiguity, the capacitance C_3 at switch C port 5 is used as a third, highly reflective impedance. With a normalized susceptance ($b_{\mathrm{C}_3} = 50\,\Omega \cdot \omega C_3$), $\underline{r}_\mathrm{x}$ can be calculated as described in [5]. Substituting $\underline{r}_\mathrm{x}$ into (3) yields the differential voltage ($\Delta V_\mathrm{out} = V_{\mathrm{C}_3}$) and a third circular equation with the radius R_{C_3}:

$$R_{\mathrm{C}_3}^2 = \left(\frac{V_\mathrm{x}}{V_{\mathrm{C}_3}}\right)^2 = \left(X_{\mathrm{C}_3} - \mathrm{Re}\{\underline{r}_\mathrm{LNA}\}\right)^2 + \left(Y_{\mathrm{C}_3} - \mathrm{Im}\{r_\mathrm{LNA}\}\right)^2 \tag{6}$$

With

$$X_{\mathrm{C}_3} = \frac{1-b_{\mathrm{C}_3}^2}{1+b_{\mathrm{C}_3}^2}, Y_{\mathrm{C}_3} = \frac{2b_{\mathrm{C}_3}}{1+b_{\mathrm{C}_3}^2}. \tag{7}$$

The circles corresponding to the three circle equations (4), (5) and (6) are presented in Fig. 2. An examination of the circles defined in (4) and (5) confirms that they are insufficient to determine $\underline{r}_\mathrm{LNA}$. They intersect at two points, such that the imaginary part cannot be uniquely determined. The inclusion of the third circle (6) enables, by varying V_x and the resulting adjustment of the radii of all circles to achieve a single, common intersection point in the complex plane of $\underline{r}_\mathrm{LNA}$. V_x then satisfies all circle equations, and $\underline{r}_\mathrm{LNA}$ is determined by the coordinates of this point.

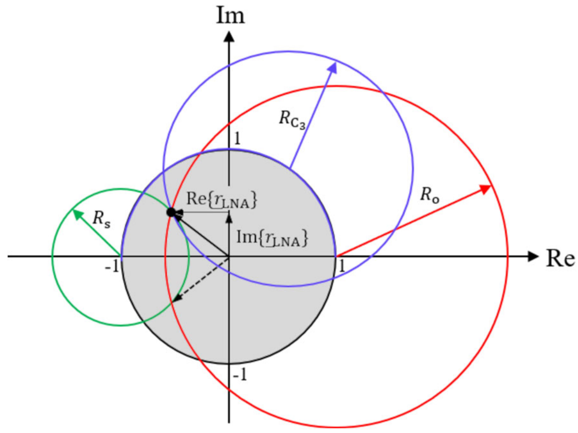


Fig. 2. Visualization of the three circular equations in the complex plane of the LNA's reflection coefficient. Open (red) centered at 1 on the real axis, Short (green) centered at -1 on the real axis and Capacitance (blue) centered on the unit circle in the upper complex half plane

Once $\underline{r}_\mathrm{LNA}$ is mathematically characterised, the frequency-dependent input impedance of the amplifier $\underline{Z}_\mathrm{LNA}$ can be calculated (8). This enables compensation for the voltage divider effect when calculating the object temperature.

$$\underline{Z}_\mathrm{LNA} = 50\,\Omega \cdot \frac{1+\underline{r}_\mathrm{LNA}}{1-\underline{r}_\mathrm{LNA}} \tag{8}$$

III. Conclusion

Assuming an ideal 50 Ω LNA input impedance introduces a significant error in the targeted wideband radiometry application. The proposed mathematical extension provides an in-situ method to dynamically quantify the LNA's complex reflection coefficient through the use of a three-impedance Open-Short-Capacitance calibration method and resolving the resultant intersecting circles in the complex plane. This advancement enables the accurate determination of the temperature of an object in a cavity, even when the LNA exhibits a frequency-dependent, non-ideal input impedance.

Acknowledgment

This work was supported by the BMBF Program FHKooperativ, Project NoCRaFT (13FH034KX1). The LLM-Tools Grammarly, Gemini and DeepL were used to correct and improve language.

References

[1] F. Ströder and K. Thelen, "Design of a Self-Calibrating Wide-Band Radiometer," in *2023 International Workshop on Impedance Spectroscopy (IWIS)*, Chemnitz, Germany, 2023, pp. 125–128.

[2] J. Detlefsen and U. Siart, *Grundlagen der Hochfrequenztechnik,* 4th ed. München: Oldenbourg, 2012. [Online]. Available: http://www.oldenbourg-link.com/isbn/9783486708912

[3] S. G. Vesnin, M. Sedankin, V. Leushin, V. Skuratov, I. Nelin, and A. Konovalova, "Research of a microwave radiometer for monitoring of internal temperature of biological tissues," *EEJET*, vol. 4, 5 (100), pp. 6–15, 2019, doi: 10.15587/1729-4061.2019.176357.

[4] V. Thomy, L. Dubois, C. Vanoverschelde, J. P. Sozanski, and J. Pribetich, "Radiometric Sensor for Temperature Control of Food Processing," *IEEE Sensors J.*, vol. 4, no. 6, pp. 772–778, 2004, doi: 10.1109/JSEN.2004.833146.

[5] K. Küpfmüller, *Theoretische Elektrotechnik: Eine Einführung,* 18th ed. Berlin, Heidelberg: Springer, 2008.

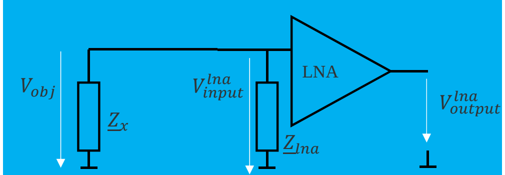
In-Situ Input Impedance Determination of Low Noise Amplifiers in Radiometric Applications

Dominik Kraft[1], Fabian Ströder[1,2], Daniel Erni[2], Klaus Thelen[1]

(1) Institute of Measuring and Sensor Technology, Ruhr West University of Applied Science, Mülheim an der Ruhr, Germany
(2) General and Theoretical Electrical Engineering (ATE), University of Duisburg-Essen, and Center for Nanointegration Duisburg-Essen (CENIDE), D-47048 Duisburg, Germany

NEVER STOP GROWING

Radiometric Thermometry



- **Temperature information is contained in the noise voltage**

$$V_{obj} = \sqrt{4 k_B T_{Obj} Re\{\underline{Z}_x\} \Delta f} \quad (1)$$

- **Voltage at the LNA input:**

$$V_{input}^{lna} = \left| \frac{\underline{Z}_{lna}}{\underline{Z}_{lna} + \underline{Z}_x} \right| \cdot V_{obj} \quad (2)$$

- **Voltage at the LNA output:**

$$V_{output}^{lna} = \left| \frac{\underline{S}_{21}^{lna}}{1 + \underline{S}_{11}^{lna}} \right| \cdot V_{input}^{lna} \quad (3)$$

kB: Boltzmann's constant
Δf: resolution bandwidth
T_{Obj}: Temperature within the object
Z_{ant}: Impedance of the system
Z_{lna}: Input impedancee of the LNA
Z_0: Reference impedance of the measurement instrument (50 Ω)

Core Principle

- Object temperature is proportional to its emitted thermal noise power.

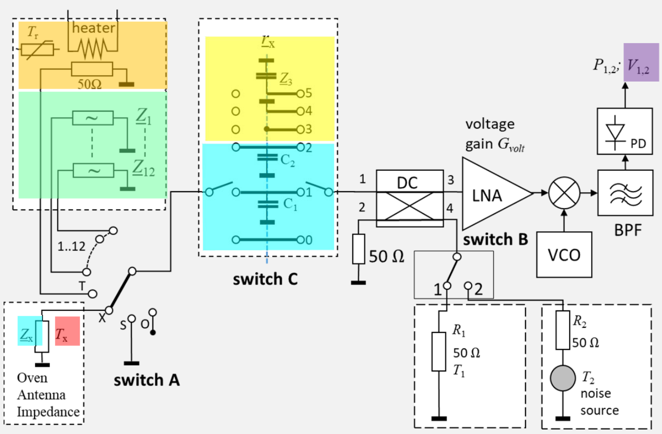
Key Challenge

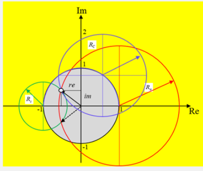
- LNA input impedance varies with time and temperature, altering the voltage divider ratio.
- Without accurate compensation, the calculated object temperature contains significant error.

NEVER STOP GROWING

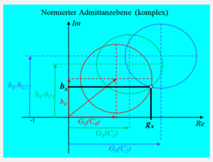
Setup

$$\underline{T}_x = \frac{\underline{V}_o^2 \cdot \left|\frac{\underline{Z}_x + \underline{Z}_{LNA}}{\underline{Z}_x}\right|^2 - |\underline{V}_n|^2 - |\underline{I}_n|^2 \cdot |\underline{Z}_x|^2 - 2 \cdot \mathrm{Re}\{\underline{Z}_{ant}\} \cdot \mathrm{Re}\{\underline{I}_n \cdot \underline{V}_n^*\} - 2\,\mathrm{Im}\{\underline{Z}_x\} \cdot \mathrm{Im}\{\underline{I}_n \cdot \underline{V}_n^*\}}{\underline{G}_{volt}^2 \cdot 4k\Delta f\,\mathrm{Re}\{\underline{Z}_x\}}$$

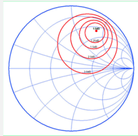




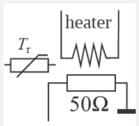
6 sweeps
$\Rightarrow \underline{Z}_{LNA}$; V_x



6 sweeps
$\Rightarrow \underline{Z}_{ant}$



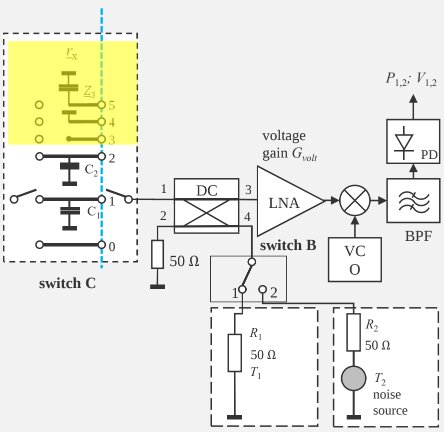
6n sweeps: (n = no. of noise impedances)
$\Rightarrow |\underline{I}_n|^2$; $\mathrm{Re}(\underline{I}_n \underline{V}_n^*)$; $\mathrm{Im}(\underline{I}_n \underline{V}_n^*)$;

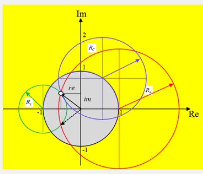


2 sweeps
@ 2 temperatures
$\Rightarrow G_{volt}$, V_n

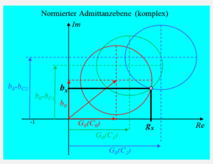
Setup

$$\underline{T}_x = \frac{\underline{V}_o^2 \cdot \left|\frac{\underline{Z}_x + \underline{Z}_{LNA}}{\underline{Z}_x}\right|^2 - |\underline{V}_n|^2 - |\underline{I}_n|^2 \cdot |\underline{Z}_x|^2 - 2 \cdot \mathrm{Re}\{\underline{Z}_{ant}\} \cdot \mathrm{Re}\{\underline{I}_n \cdot \underline{V}_n^*\} - 2\,\mathrm{Im}\{\underline{Z}_x\} \cdot \mathrm{Im}\{\underline{I}_n \cdot \underline{V}_n^*\}}{\underline{G}_{volt}^2 \cdot 4k\Delta f\,\mathrm{Re}\{\underline{Z}_x\}}$$

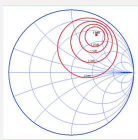




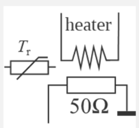
6 sweeps
$\Rightarrow \underline{Z}_{LNA}$; V_x



6 sweeps
$\Rightarrow \underline{Z}_{ant}$



6n sweeps: (n = no. of noise impedances)
$\Rightarrow |\underline{I}_n|^2$; $\mathrm{Re}(\underline{I}_n \underline{V}_n^*)$; $\mathrm{Im}(\underline{I}_n \underline{V}_n^*)$;



2 sweeps
@ 2 temperatures
$\Rightarrow G_{volt}$, V_n

HOCHSCHULE RUHR WEST
UNIVERSITY OF APPLIED SCIENCES
INSTITUTE FOR MEASUREMENT ENGINEERING AND SENSOR TECHNOLOGY

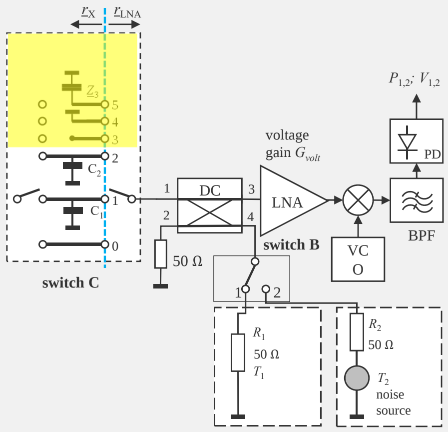
Principle of measurement

$$a_{1,2}^{0} = \beta \cdot \sqrt{T_{1,2} \cdot k_B \cdot \Delta f} \longrightarrow V_x = G \cdot \sqrt{(a_2^0)^2 - (a_1^0)^2} \longrightarrow V_{out} \approx V_x \cdot \left| \frac{r_x}{1 - r_x r_{LNA}} \right| + V_{int}$$

$$b_{1,2}^{tot} = a_{1,2}^{0} \cdot \left| \sum_{n=1}^{\infty} r_x^n \cdot r_{LNA}^{n-1} \right| = a_{1,2}^{0} \cdot \left| \frac{r_x}{1 - r_x \cdot r_{LNA}} \right|$$

V_{int}: impedance-dependent, intrinsic noise of the LNA

$$\Delta V_{out} = \sqrt{{V_2}^2 - {V_1}^2} = V_x \cdot \left| \frac{r_x}{1 - r_x r_{LNA}} \right|$$

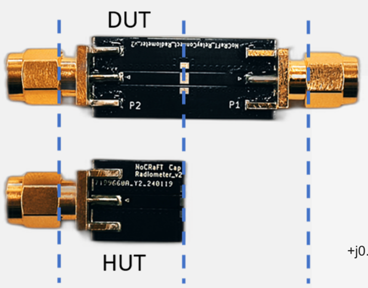


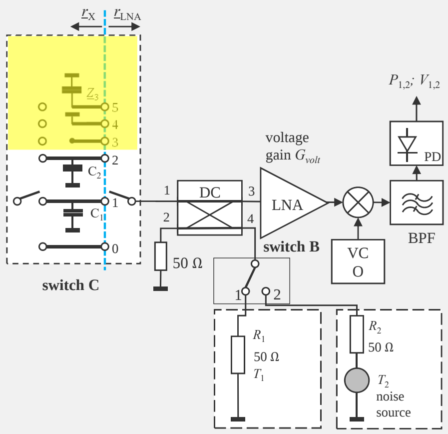
- Noise voltage measured with a spectrum analyser during setup
- V_x is an unknown parameter
- Subtracting uncorrelated voltages V_1 and V_2
- Intrinsic noise of the LNA and impedance noise of the HUTs eliminated

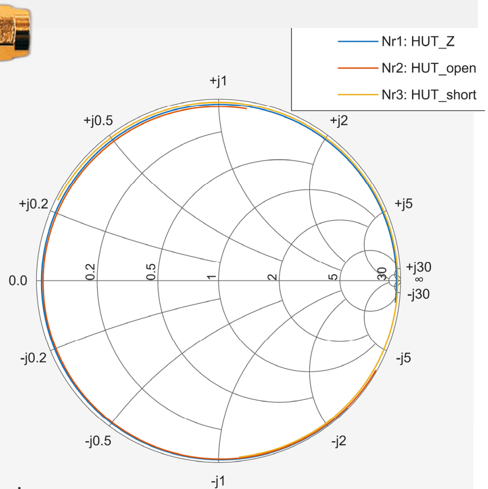
HOCHSCHULE RUHR WEST
UNIVERSITY OF APPLIED SCIENCES
INSTITUTE FOR MEASUREMENT ENGINEERING AND SENSOR TECHNOLOGY

Principle of measurement

- Symmetrical PCBs as DUT connections (needed for determination of target impedance)
- PCB with half the length (HUT) as an open circuit, short circuit and with a shunt capacitor
- S-parameters measured in advance with VNA







$$\Delta V_{out} = \sqrt{{V_2}^2 - {V_1}^2} = V_x \cdot \left| \frac{r_x}{1 - r_x r_{LNA}} \right|$$

Determination of LNA impedance / LNA reflection coefficient

- Sought: Input impedance of the LNA $\underline{Z}_{LNA}$ or the LNA reflection factor $\underline{r}_{LNA}$. The following applies: $\underline{r}_{LNA} = re + j \cdot im = \frac{\underline{Z}_{LNA} - 50\ \Omega}{\underline{Z}_{LNA} + 50\ \Omega}$
- The HUT measurements (open/short/C) result in three circuit equations in the reflection plane.

Solution in 3 steps:

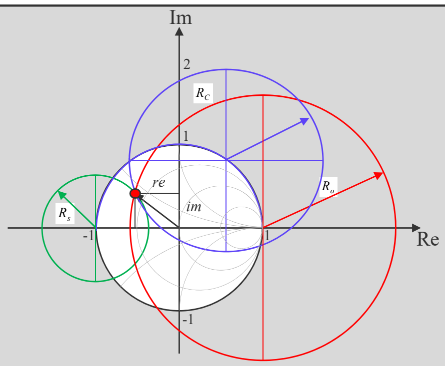
Step 1:
Determination of the circle equations:

Short: $$R_s^{\ 2} = (1 + re)^2 + im^2 = \frac{V_x^{\ 2}}{V_s^{\ 2}}$$ $Y_i =$ [illegible]

Open: $$R_o^{\ 2} = (1 - re)^2 + im^2 = \frac{V_x^{\ 2}}{V_o^{\ 2}}$$ $Y_i = 0$

C: $$R_{Z3}^{\ 2} = (X_{Z3} - re)^2 + (Y_{Z3} - im)^2 = \frac{V_x^{\ 2}}{V_{Z3}^{\ 2}}$$ $Y_i = G_i + j \cdot B_i$

Where the centre points of circles are: $$X_{Zi} = \frac{Z_0^{-1} - G_i^{\ 2} - B_i^{\ 2}}{(Z_0^{-1} - G_i)^2 + B_i^{\ 2}}; \quad Y_{Zi} = \frac{2B_i}{(Z_0^{-1} - G_i)^2 + B_i^{\ 2}};$$



- Centres are known, calibration voltage V_X is unknown => V_X is selected, so that an intersection exists
- Ideally, the centres of the circles lie on the unit circle (C), at [-1;0] (short) and at [1;0] (open).
- All three circles must have exactly ONE common intersection.
- This results in the calibration voltage Vx, which is proportional to the radii and will be used later.

Determination of LNA impedance / LNA reflection coefficient

Step 2:
Combining two circle equations to form one => elimination of calibration voltage Vx.

Short: $$R_s^{\ 2} = (X_S - re)^2 + (Y_S - im)^2 = \frac{V_x^{\ 2}}{V_s^{\ 2}}$$

Open: $$R_o^{\ 2} = (X_o - re)^2 + (Y_o - im)^2 = \frac{V_x^{\ 2}}{V_o^{\ 2}}$$

C: $$R_{Z3}^{\ 2} = (X_{Z3} - re)^2 + (Y_{Z3} - im)^2 = \frac{V_x^{\ 2}}{V_{Z3}^{\ 2}}$$

$$(re - X_{os})^2 + (im - Y_{os})^2 = R_{os}^{\ 2}$$

$$(re - X_{oC})^2 + (im - Y_{oC})^2 = R_{oC}^{\ 2}$$

where:

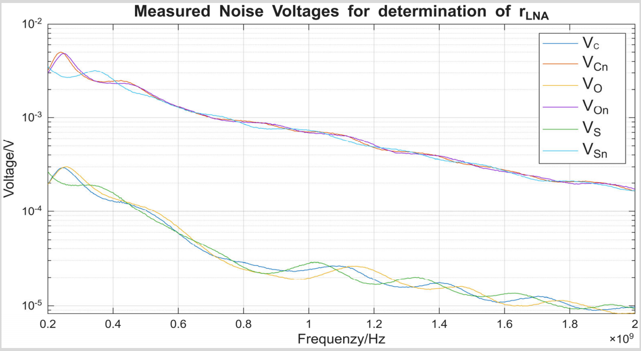
$$X_{os} = \frac{X_o \frac{V_o^{\ 2}}{V_s^{\ 2}} - X_s}{\frac{V_o^{\ 2}}{V_s^{\ 2}} - 1}; \quad B_{os} = \frac{X_o^{\ 2} \frac{V_o^{\ 2}}{V_s^{\ 2}} - X_s^{\ 2}}{\frac{V_o^{\ 2}}{V_s^{\ 2}} - 1}; \quad Y_{os} = \frac{Y_o \frac{V_o^{\ 2}}{V_s^{\ 2}} - Y_s}{\frac{V_o^{\ 2}}{V_s^{\ 2}} - 1}; \quad D_{os} = \frac{Y_o^{\ 2} \frac{V_o^{\ 2}}{V_s^{\ 2}} - Y_s^{\ 2}}{\frac{V_o^{\ 2}}{V_s^{\ 2}} - 1}; \quad R_{os}^{\ 2} = X_{os}^{\ 2} - B_{os} + Y_{os}^{\ 2} - D_{os}$$

$$X_{oC} = \frac{X_o \frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - X_{Z3}}{\frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - 1}; \quad B_{oC} = \frac{X_o^{\ 2} \frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - X_{Z3}^{\ 2}}{\frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - 1}; \quad Y_{oC} = \frac{Y_o \frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - Y_{Z3}}{\frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - 1}; \quad D_{oC} = \frac{Y_o^{\ 2} \frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - Y_{Z3}^{\ 2}}{\frac{V_o^{\ 2}}{V_{Z3}^{\ 2}} - 1}; \quad R_{oC}^{\ 2} = X_{oC}^{\ 2} - B_{oC} + Y_{oC}^{\ 2} - D_{oC}$$

Determination of LNA impedance / LNA reflection coefficient

Raw Data

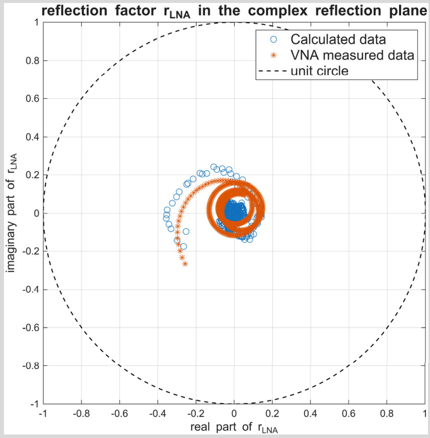
- Noise voltage measured with SA during setup



with r_{HUT} →

Calculated Data

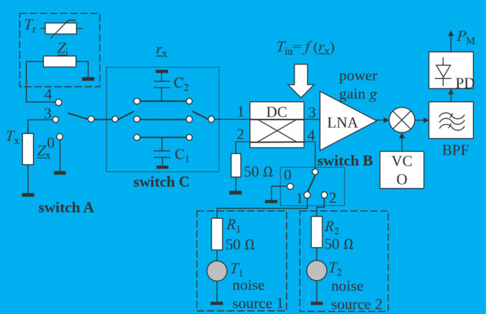
- Reflection factor of LNA input



NEVER STOP GROWING

HRW HOCHSCHULE RUHR WEST UNIVERSITY OF APPLIED SCIENCES

Conclusion



Problem addressed

- Assuming ideal 50Ω LNA impedance introduces significant error in wideband radiometry.

Method introduced

- Open–Short–Capacitance three-impedance calibration with intersecting-circle resolution in the complex plane.

Outcome

- Object temperature determination enabled even with frequency-dependent, non-ideal LNA input impedance.

Supported by BMBF Program FH-Kooperativ, Project NoCrAFT (13FH034KX1)

NoCRaFT

NEVER STOP GROWING

HOCHSCHULE RUHR WEST
UNIVERSITY OF APPLIED SCIENCES

Thank you for your attention!

NEVER STOP GROWING

Determination of LNA impedance / LNA reflection coefficient

Step 3:
Calculation of the 2 intersection points and selection

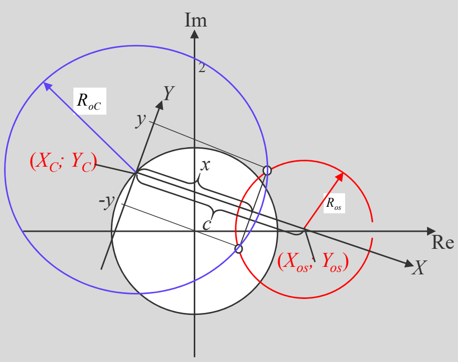
Open/Short: $\boxed{(re - X_{os})^2 + (im - Y_{os})^2 = R_{os}^{\ 2}}$

Open/C: $\boxed{(re - X_{oC})^2 + (im - Y_{oC})^2 = R_{oC}^{\ 2}}$

Intersection 1: $\boxed{re_1 = X_{oC} + x \cdot \frac{X_{os} - X_{oC}}{c} - y \cdot \frac{Y_{os} - Y_{oC}}{c};\ \ im_1 = Y_{oC} + x \cdot \frac{Y_{os} - Y_{oC}}{c} + y \cdot \frac{X_{os} - X_{oC}}{c};}$

Intersection 2: $\boxed{re_2 = X_{oC} + x \cdot \frac{X_{os} - X_{oC}}{c} + y \cdot \frac{Y_{os} - Y_{oC}}{c};\ \ im_2 = Y_{oC} + x \cdot \frac{Y_{os} - Y_{oC}}{c} - y \cdot \frac{X_{os} - X_{oC}}{c};}$

where: $\boxed{c = \sqrt{(X_{os} - X_{oC})^2 + (Y_{os} - Y_{oC})^2};\ \ x = \frac{c^2 - R_{os}^{\ 2} + R_{oC}^{\ 2}}{2c};\ \ y_{1,2} = \sqrt{R_{oC}^{\ 2} - x^2}}$



Selection:
- The intersection point within the unit circle is selected.
- For ideal components (open/short/C), the other point lies outside the unit circle.

SENSORICA 2026

The Institute of Measurement and Sensor Technology is pleased to invite junior and established scientists working in the fields of industrial and medical metrology, as well as RF and microwave electronics, to the 11th International Workshop at the MST Institute. The workshop will be held at the Ruhr West University of Applied Sciences
in **Mülheim Ruhr, Germany,**
on **June 18th and 19th**, 2026.

Registration free of charge

Visit us at:
sensorica.hs-ruhrwest.de

The conference is aimed at contributions with innovative solutions from the RF and Microwave, medical and industrial measurement sectors. This includes (but is not limited to) technologies such as:

-Impedance Spectroscopy	-Non-invasive measurements
-Automotive Sensors	-Radiometry
-Optical Sensors	-RF & Microwave Sensors
-Quantum Sensors	-Radar Applications
-Sensor Networks	-Environmental Measurement
-Sensor Data Processing	-Novel Sensor Principles

The venue is located in the heart of the Ruhrgebiet. It has a rich industrial heritage and cultural significance. Today, it offers a diverse range of attractions such as UNESCO World Heritage Sites, art galleries, museums, theatres, outdoor activities, lively markets, delicious cuisine and vibrant nightlife. The Ruhrtourismus GmbH has built a platform and service to present a large variety of cultural activities. https://www.ruhr-tourismus.de

Venue:
Hochschule Ruhr West
Institut Mess- und Sensortechnik
Duisburger Str. 100
45479 Mülheim an der Ruhr

Förderverein Hochschule Ruhr West · Institut Mess- und Sensortechnik · HRW Hochschule Ruhr West University of Applied Sciences · Universität Duisburg-Essen Open-Minded · CENIDE Center for Nanointegration Duisburg-Essen · Universität Siegen · ZESS · Technische Universität Chemnitz · Wayne State University · VDI