

Calibration of DORA RF payload

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1. INTRODUCTION

Instrument calibration checks and adjusts measurement accuracy to ensure reliable and consistent results. Calibration is the process of comparing measurements of an instrument to a known standard reference and making adjustments in the instrument to make the measurements close to the standard reference. DORA RF payload is an integrated 8-channel RF power detector using eight separate band pass filters, frequencies ranging from 30 to 190 MHz, each channel with a bandwidth of 20 MHz. The integrated RF power is detected by connecting each channel through RF switches to a detector. DORA RF receiver uses the logarithmic power detector to measure the RF power. The logarithmic relationship between the input power and the output voltage or current is the basis for how the logarithmic detector functions. With just one device, the detector can precisely monitor a wide dynamic range of RF power levels, from very low to high powers. Logarithmic detectors offer a logarithmic response that retains linearity across a wider range of input powers, unlike linear detectors, which may saturate or become nonlinear at high power levels. The detector's sensitivity to low power levels is improved by this logarithmic response, enabling accurate readings even at weak signal intensities. Furthermore, logarithmic detectors frequently have a quick response time, which qualifies them for use for real-time power monitoring or control.

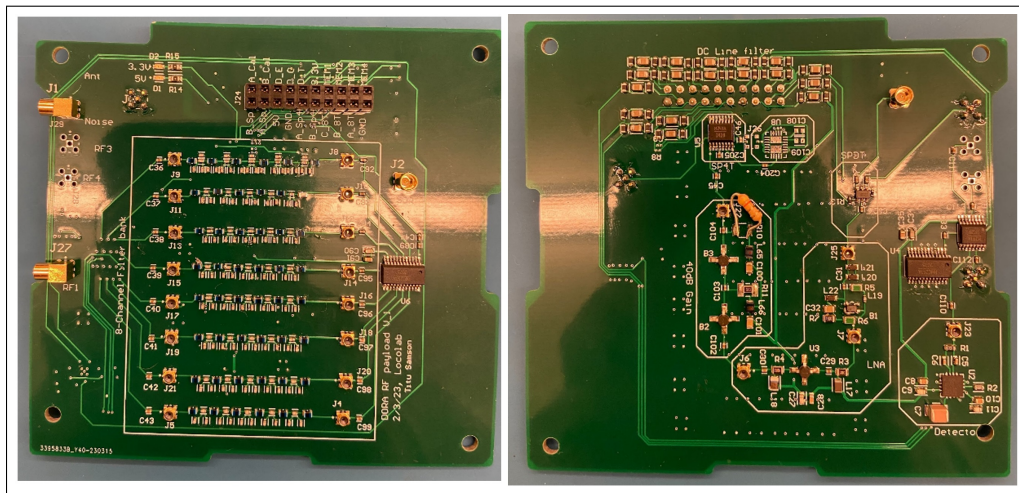


Fig. 1. DORA RF payload PCB top and bottom

DORA RF payload is a double-sided PCB with a series of switches, gain blocks, bandpass filters, and detectors. Figure 1 shows the top and bottom sides of the DORA RF payload.

2. SLOP AND INTERCEPT CALCULATION FROM DATASHEET

In the data sheet of AD8318(detector), the calibration process uses the slope and intercept method. Applying known reference power levels to the detector and measuring the related output voltage are the first steps in calibrating an RF power detector utilizing the slope and intercept approach. Plot the data points on a graph with the reference power levels on the x-axis and the detector output readings on the y-axis. Calculate the slope of the best-fit line, which represents the ratio of input power to detector output, using linear regression. Calculate the intercept of the line as well, which indicates any bias or offset in the detector's response. The RF power detector can offer accurate and trustworthy power readings for a range of input signal levels by modifying subsequent power measurements using the obtained slope and intercept values. According to the

datasheet, the detector will operate linearly for input power ranging from -5 dBm to -55 dBm. A series of measurements are made in channel 1 for various input powers to determine the slope and intercept of the linear region.

Pin1=-4.03 dBm, Pin2 = -26.725 dBm, Vout1=1.3907V, Vout2= 1.9103V

Calculated slope= -0.02289, intercept =56.71276

Pin(unknown)= Vout(measured)/slope + intercept

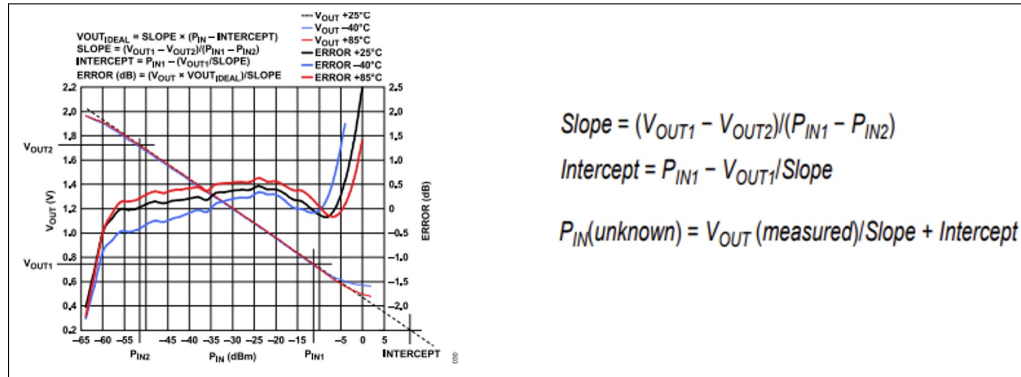


Fig. 2. Slop and intercept calculation method from datasheet

A noise source is connected to RF payload through an attenuator bank with different attenuation levels at 30dB, 20dB, 15dB, 10dB, and 0dB. The attenuator bank will give the flexibility of testing the payload with non-time varying noise source at different power levels. A set of measurements are taken by connecting noise source through the attenuator bank. RF power is calculated for each channel with the slope and intercept of channel 1. Figure 3 displays scatter plots and the actual spectrum of the measurements. Scatter plots display the contrast between calculated and measured RF power. Scatter plots of calibrated results show a difference in output voltage of detector for the same input power at a different frequency, which means the output voltage is frequency dependent and individual channels need to be calibrated. The result shows that slope and intercept for one channel cannot be applied to another channel.

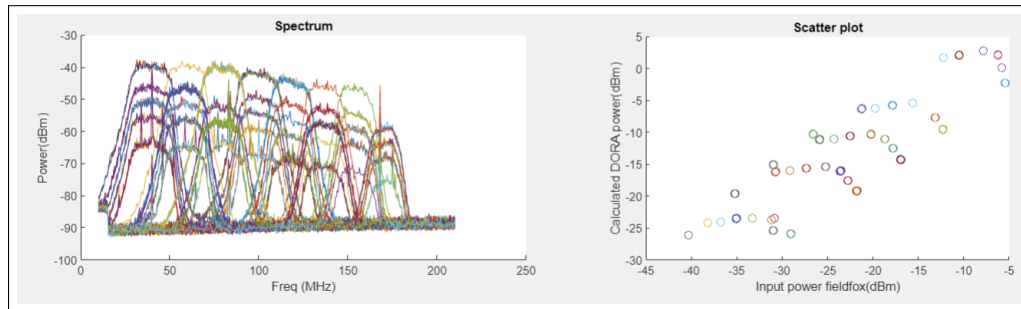


Fig. 3. Left: Spectrum of different power levels from fieldfox, Right: Scatter plot of Different noise levels at the input of RF payload calibrated with channel 1

3. CALIBRATION SETUP

To determine the calibration parameters, such as slope and intercept, with greater accuracy and precision, it is advantageous to have more measurement points. With additional data points, the calibration curve may be fitted to the collected data more precisely, reducing the chance of errors and overall improving the accuracy of the calibration. Furthermore, a greater sample size aids in accounting for any potential nonlinearity or variability in the RF detector's response, resulting in a more reliable calibration that can precisely capture the detector's behavior over a wider range of input signal intensities. As a result, adding more calibration sites improves the

Table S1. Calibration coefficient for all channels

Co-eff	Chn1	Chn2	Chn3	Chn4	Chn5	Chn6	Chn7	Chn8
P1	-42.585	-41.983	-40.953	-41.065	-40.733	-40.43	-40.124	-38.212
P2	53.806	50.274	46.396	44.228	41.803	39.96	38.058	33.676

accuracy and efficiency of the calibration procedure. A switch connects a noise source/antenna to the RF payload's input through five different attenuation levels to obtain more data points for calibration. The voltage output from the detector is sampled using the ADC in Arduino. RF power is measured using the channel measurement option in fieldfox. The actual spectrum was also measured using fieldfox for comparison. The calibration setup is shown in Figure 4. The calibration process is automated using MATLAB and Arduino.

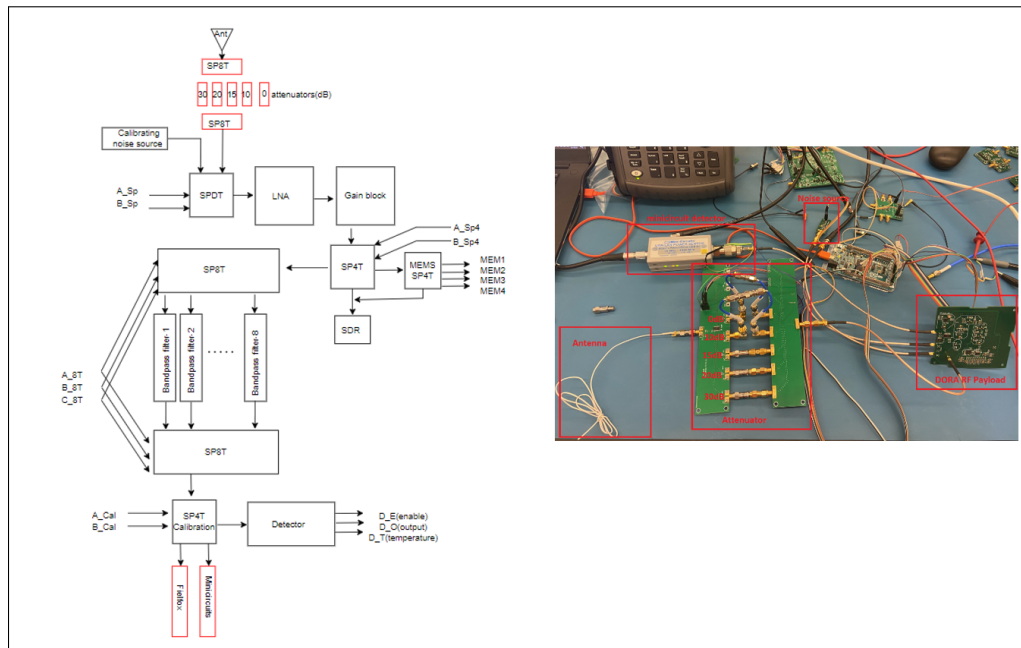


Fig. 4. Calibration setup Left: block diagram and Right: measurement setup

A. Channel 1 calibration

Fitting a first-degree polynomial is a common calibration technique that provides a straightforward equation for establishing the link between input and output quantities. A series of calibration data points can be used to do a linear regression analysis, where the device measures the corresponding output values and the input values act as known reference values. By reducing the overall distance between the data points and the line, the analysis can find the line that fits the data the best. The calibration equation, which is commonly expressed as $y = P1x + P2$, results from the line's resulting equation, where P1 stands for the gain factor or slope and P2 for the offset or y-intercept. A first-degree polynomial is fit with the channel 1 data using MATLAB to calculate the coefficients as shown in the figure 5. Similarly, co-efficient are calculated for all channels. Polynomial fit for all other channels are shown in the appendix.

Calculated calibration coefficients are shown in the table S1 for all channels. The unknown input power can be calculated as below.

$$\text{Power(dBm)} = P1 * \text{Detector voltage} + P2$$

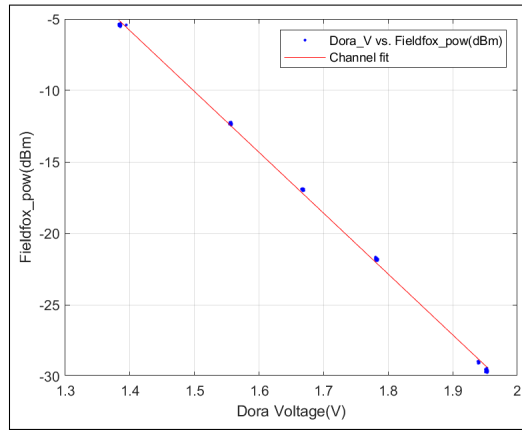


Fig. 5. Fitting a first-degree polynomial to channel 1 data

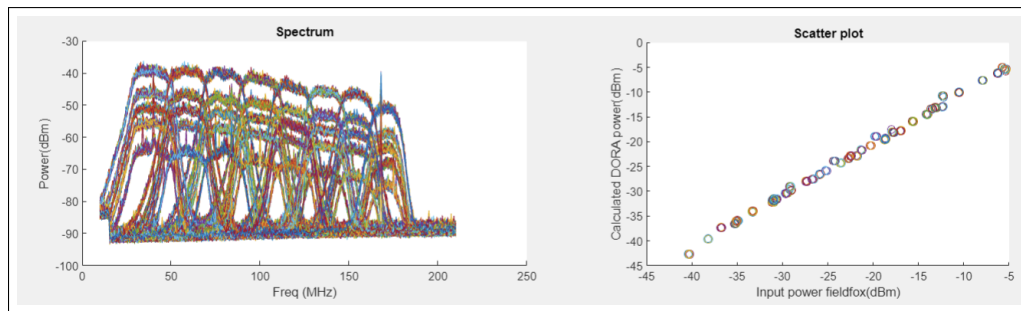


Fig. 6. Left: Spectrum of noise source with different power level, Right: Scatter plot after calibrating with individual channel coefficients

4. LINEAR REGRESSION ANALYSIS OF CALIBRATION DATA

Figure 7 shows the result of regression analysis of calibration data for all channels. A p-value of zero indicates that the regression analysis revealed highly significant results. This shows that there is no chance factor in the relationship between the independent variable (X) and the dependent variable (Y). The model's predictions are, on average, only 0.475 dBm off from the actual values of Y, as shown by the root mean square (RMS) value of 0.475. Furthermore, the high R-squared value of 0.997 shows that variations in X account for 99.7% of the variability in Y. These results emphasize the model's capability to predict Y precisely based on X and show a strong and exact link between X and Y.

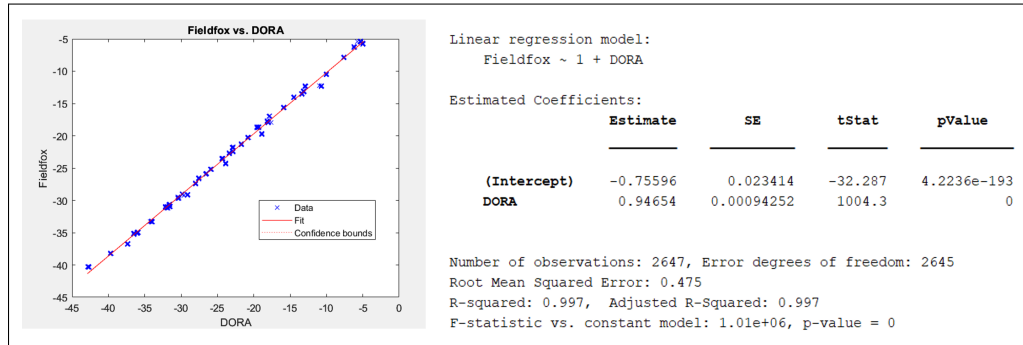


Fig. 7. Regression analysis of calibrated data

5. OUTDOOR MEASUREMENT

A telescopic monopole antenna that resonates at about 90 MHz is attached to the RF payload for outdoor measurements and power bank supplies 5V DC to the payload. To test the actual power and spectrum for comparison, a Fieldfox spectrum analyzer is connected to the measurement setup. The antenna is connected to the RF payload through attenuators of 30 dB, 15 dB, and 0 dB to observe various power levels. The figure 8 presented shows the spectrum and scatter plot for all outdoor measurements after calibration. Figure 8 shows the spectrum and scatter plot for all outdoor measurements. Figure 9 Shows the spectrum and scatter plot for outdoor measurements with three different attenuator levels. The dots in the left spectrum corresponding channel power measurement from DORA detector for three attenuation levels.

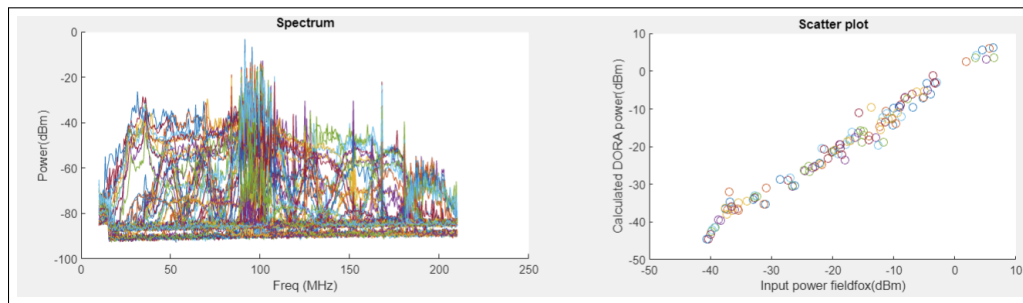


Fig. 8. Left: Spectrum of all outdoor measurements, Right: Scatter plot measured and calculated power for all outdoor measurements

6. REGRESSION ANALYSIS OF OUTDOOR MEASUREMENT

Figure 10 shows the result of the regression analysis of calibration data. The low p-value of $1.8e-102$ indicates how significant the regression analysis outcome is. This shows that there is no chance factor in the relationship between the independent variable (X) and the dependent variable (Y). The model's predictions typically differ from the actual values of Y by 1.94 dBm, as

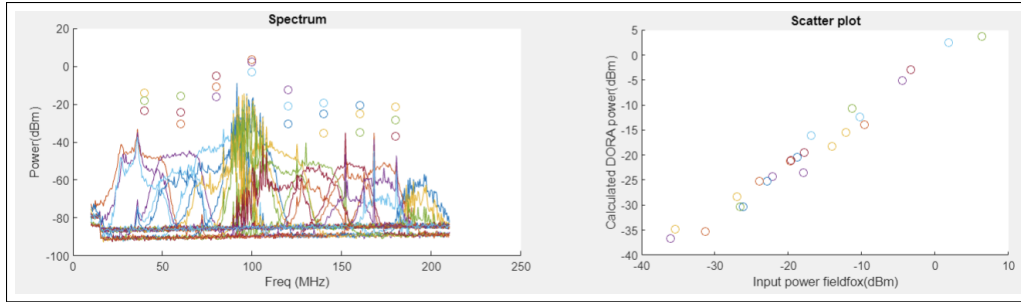


Fig. 9. Left: Spectrum of outdoor measurements with 0dB, 15dB, 30dB attenuation, Right: Scatter plot measured and calculated power for different attenuation

shown by the root mean square (RMS) value of 1.94. Additionally, the high R-squared value of 0.977 indicates that alterations in X may account for around 97.7% of the variation in Y. These results show a significant and consistent correlation between X and Y. The regression model correctly predicted Y when given the correct value of X, proving its predictive accuracy.

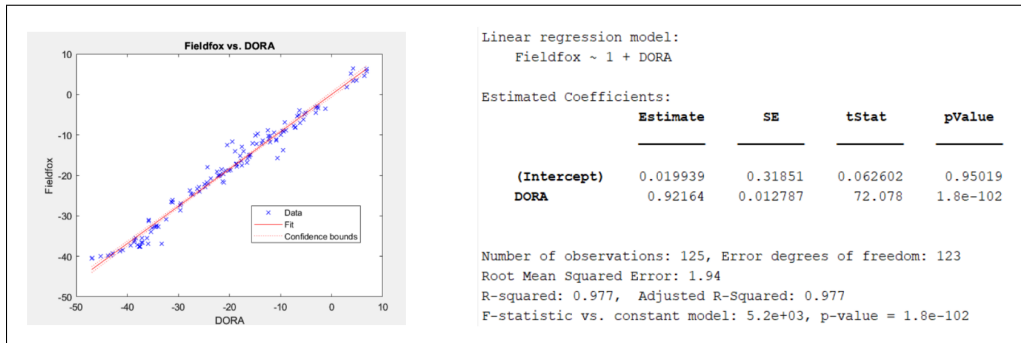


Fig. 10. Regression analysis of outdoor measurement

7. STEPS FOR CALIBRATION

A. Connect noise source through attenuator bank

The noise source is connected to the attenuator bank which will switch between 30dB, 20dB, 15dB, 10dB, and 0dB attenuation levels. The noise source needs a 12 V DC power supply. The port named noise in the RF payload is connected to the attenuator bank. Figure 11 shows the noise source, attenuator bank, and RF payload.

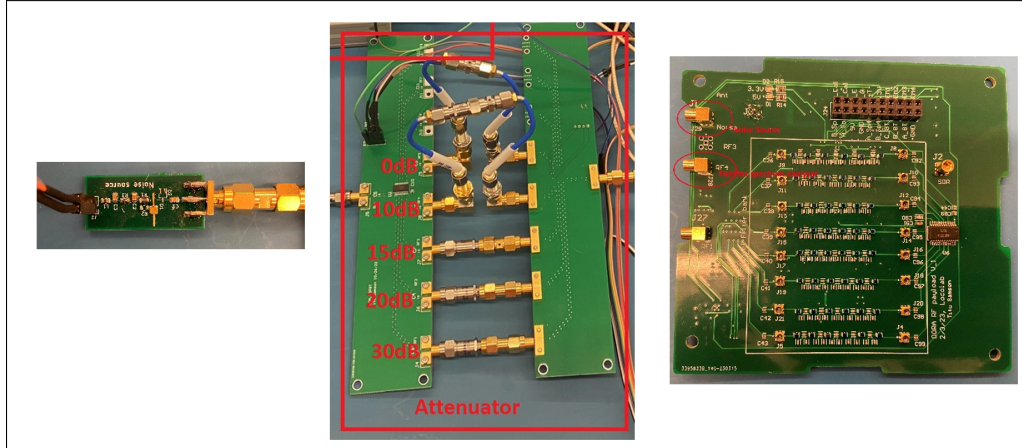


Fig. 11. Left: noise source, Middle: Attenuator bank, Right:RF payload

B. Connect Fieldfox spectrum analyzer

Connect the fieldfox spectrum analyzer to port RF4 in the RF payload. Make sure that the Fieldfox is in spectrum analyzer mode. In this calibration, Fieldfox is considered as the standard device for measuring integrated RF power and actual spectrum.

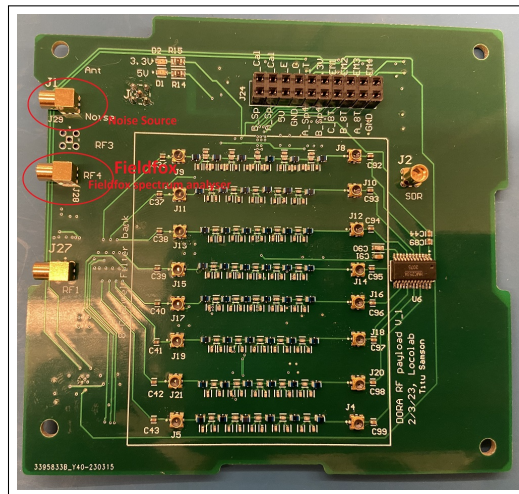


Fig. 12. Connect fieldfox spectrum analyser to the port as shown in figure

C. Connect Arduino with RF payload

Arduino is used to generate control signals to activate different RF paths with RF switches. Table S2 shows the pin mapping from arduino to RF payload. Pin number D27 to D35 is connected to RF payload. D51 to D53 is connected to antenna matching board. D30 to D40 is connected to the attenuator bank switch.

Table S2. Pin mapping of Arduino and RF payload

Pin number Arduino	RF payload pin names
D27	D_E
D39	A_Sp
D37	B_Sp
D41	A_Sp4
D43	B_Sp4
D49	A_8T
D47	B_8T
D45	C_8T
D23	B_Cal
D25	A_cal
D29	MEM_1
D31	MEM_2
D33	MEM_3
D35	MEM_4
D51	A_Match
D52	B_Match
D53	C_Match
D30	A
D32	B
D34	c
D36	A
D38	B
D40	c

Table S3. Dummy P11.csv and P22.csv for starting GUI

Co-eff	Chn1	Chn2	Chn3	Chn4	Chn5	Chn6	Chn7	Chn8
P1	-43.69	-43.69	-43.69	-43.69	-43.69	-43.69	-43.69	-43.69
P2	56.71276	56.71276	56.71276	56.71276	56.71276	56.71276	56.71276	56.71276

Also added, an additional option to enable and disable the noise source by switching the 12V DC to the noise source, which can be avoided. noise source enable/disable is controlled using pin D52.

Refer to the MATLAB function “RF_path_activation_gui.m” to change the pin mapping

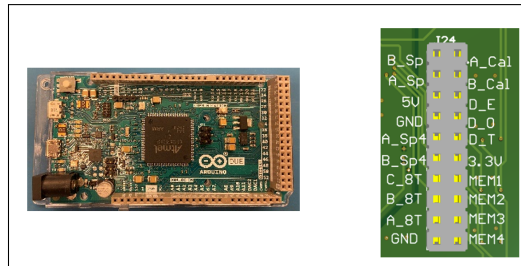


Fig. 13. Arduino and pin header of RF payload

D. Run the GUI and collect sufficient data

Before starting the GUI make sure that in the same folder of GUI there are two files ‘P11.csv’ and ‘P22.csv’. If not, make a dummy ‘P11.csv and P22.csv’ files with data shown in the table S3. MATLAB will throw errors if there are no P11.csv and P22.csv files.

Start the application by following the steps(numbering in the left figure 14), and if it responds as shown in the figure 14 right, turn the "save data button" to the "On" position and wait an hour to collect calibration data. ‘Chn_pow.csv’ and ‘Spectrum.csv’ will be automatically saved. After one-hour, press stop.

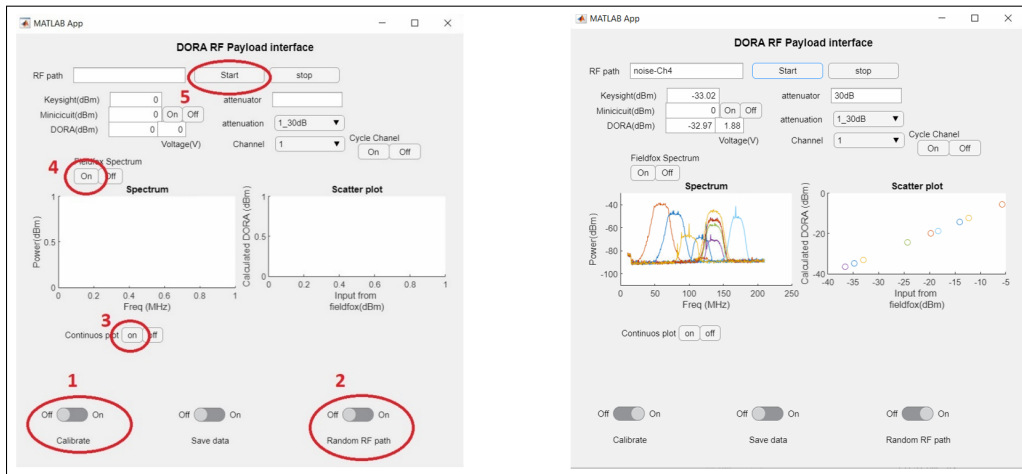


Fig. 14. Left: Shows the sequence at which buttons should be pressed Right: shows the sample plot if everything works well

Figure 15 shows the sample data of channel power measurement, col A is the RF power calculated from DORA, col B is the RF power measured from minicircuit detector if connected otherwise it will be zero, col C is the RF power measured from keysight spectrum, col D

is the DC voltage detected from DORA, col E is the channel activated, and col F is the attenuator activated. Figure 24 shows the sample Spectrum.csv file. The first row is the frequency points

A	B	C	D	E	F
-5.01	0	-3.7462	1.3811	1	1
-5.1173	0	-3.723	1.3837	1	1
-5.246	0	-3.7009	1.3867	1	1
-5.1816	0	-3.8932	1.3852	1	1
-5.1516	0	-4.0586	1.3845	1	1
-34.878	0	-35.184	1.794	18	2
-18.813	0	-18.698	1.5923	13	3

Fig. 15. Sample data of Chn_pow.csv

and the remaining rows are the spectrum measured.

	A	B	C	D	E	F	G	H	I	J
1	1.00E+07	1.05E+07	1.10E+07	1.15E+07	1.20E+07	1.25E+07	1.30E+07	1.35E+07	1.40E+07	1.45E+
2	-79.269	-77.844	-77.437	-76.784	-74.685	-70.873	-71.89	-47.098	-65.202	-66.4
3	-78.882	-78.112	-76.851	-76.793	-77.016	-68.18	-73.852	-46.123	-68.536	-66.4
4	-79.337	-79.116	-77.813	-77.334	-77.624	-71.325	-73.817	-49.709	-66.192	-64.2
5	-78.248	-76.658	-78.449	-78.425	-75.778	-68.023	-72.716	-50.878	-68.81	-64.
6	-78.612	-78.399	-75.885	-77.04	-73.922	-71.862	-70.834	-47.552	-64.668	-61.0

Fig. 16. Sample data of Spectrum.csv

After finishing the calibration measurement change the file name of Chn_pow.csv to noise_Chn_pow_calibrate.csv and Spectrum.csv to noise_Spectrum_calibrate.csv next step will use these files to generate P11.csv and P22.csv

E. Generate Calibration files P11.csv and P22.csv

Open the MATLAB app named 'Plot', press the button in the sequence as shown in the figure 17. This app will read 'noise_Spectrum_clibrate.csv', 'noise_Chn_pow_calibrate.csv', 'P11.csv', and 'P22.csv' and calibrate the channel power with P11 and P22 and save as 'Calibrated_data.csv'. 'Plot all data' button will plot all calibrated data and spectrum.

F. Files required and location

1. Dora_interface.mlapp
Functions required for this app.
 - (a) RF_path_activation_gui.m
 - (b) mini_detector.m
 - (c) Dora_detector.m
 - (d) Save_data.m
 - (e) Fieldfox_Spectrum.m
 - (f) P11.csv, P22.csv
2. Plot.mlapp
Function required for this app

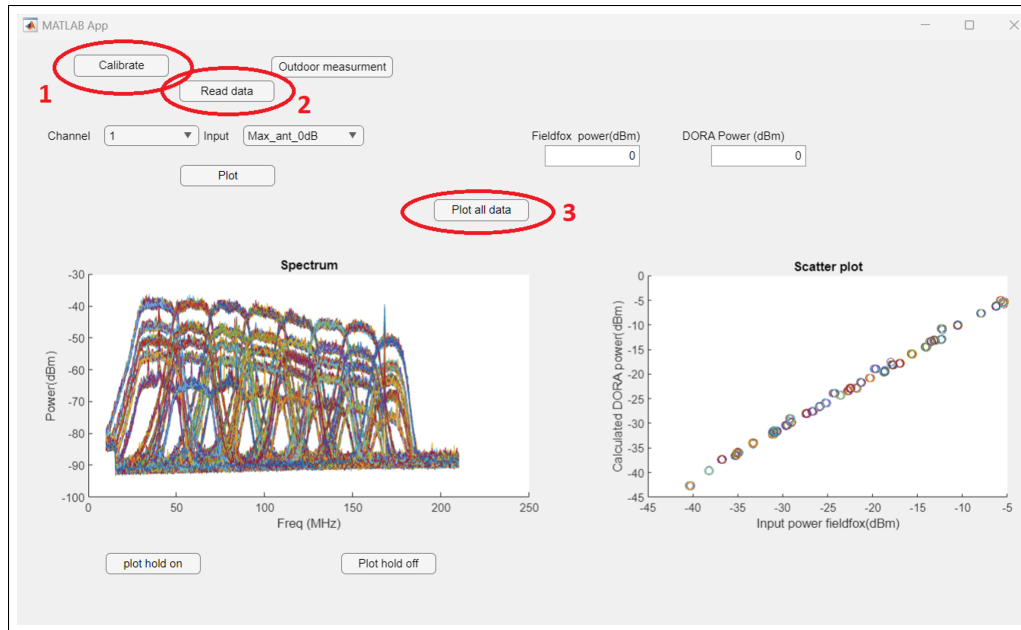


Fig. 17. Shows the sequence at which the option should be pressed

(a) createFit.m

(b) Dora_calibration.m

3. File location inside DORA google drive
 \SSTP 2019 DORA\03 Payload\RF Payload\Integrate_payload_V1_board_V1_1\MAtlab

8. APPENDIX

A. Each Channel calibration fit plots

B. Data location

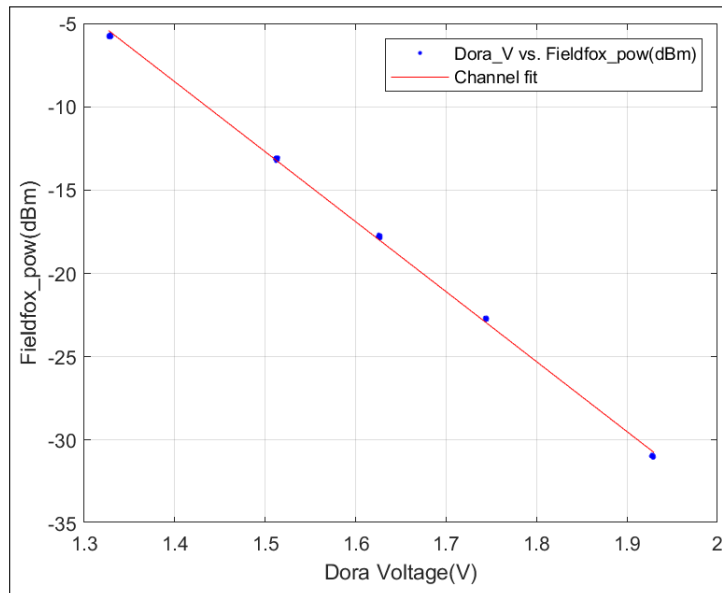


Fig. 18. Channel 2 polynomial fit plot

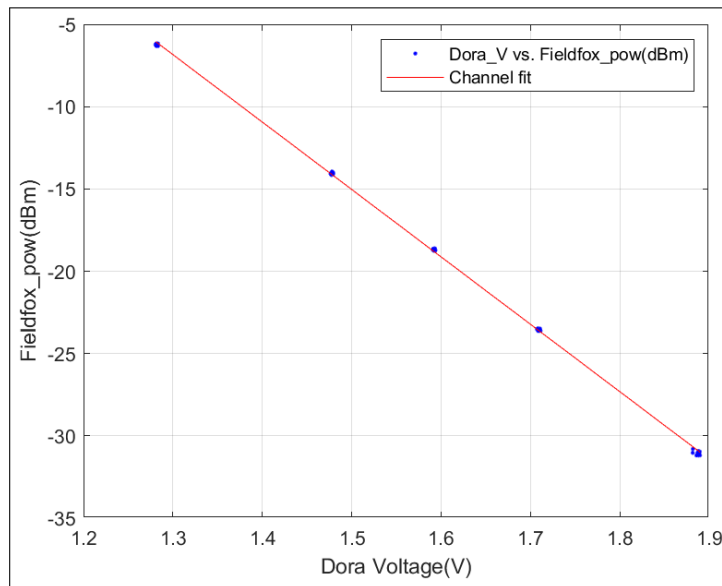


Fig. 19. Channel 3 polynomial fit plot

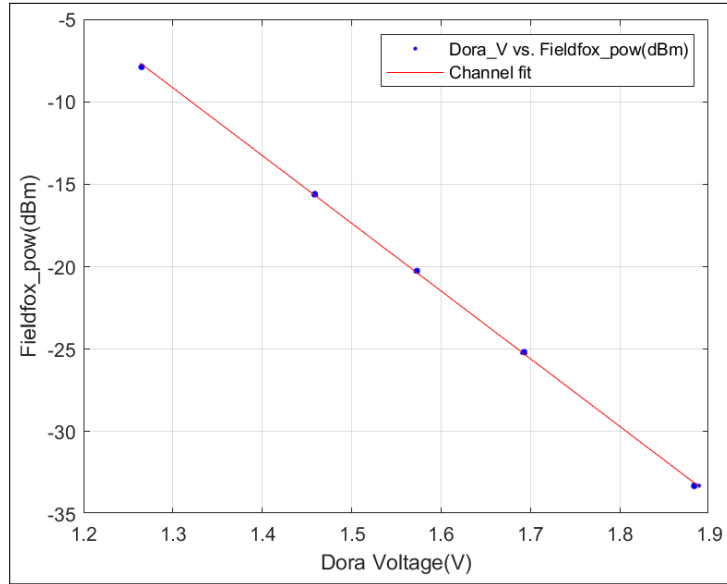


Fig. 20. Channel 4 polynomial fit plot

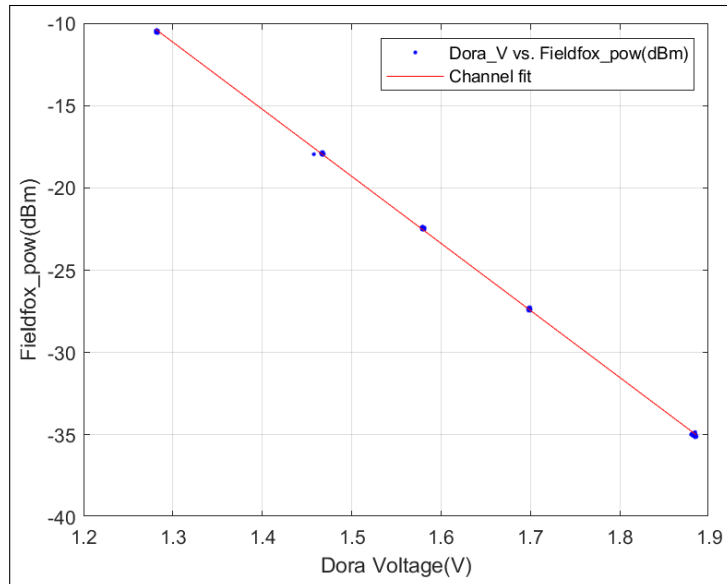


Fig. 21. Channel 5 polynomial fit plot

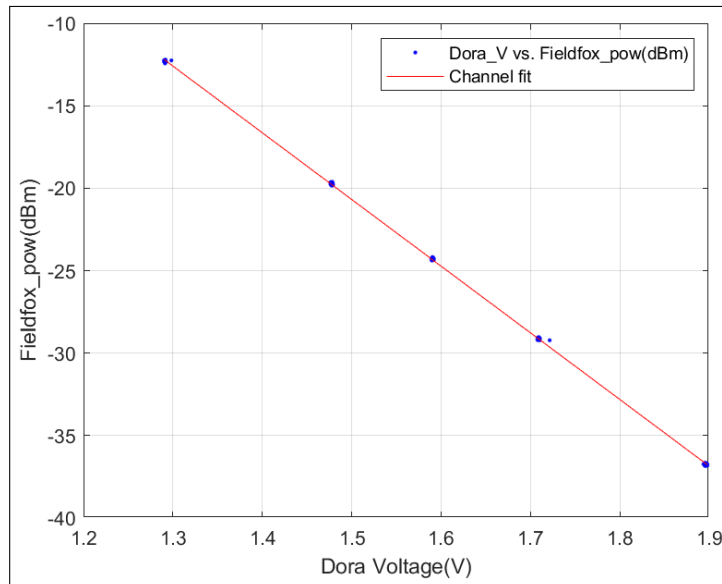


Fig. 22. Channel 6 polynomial fit plot

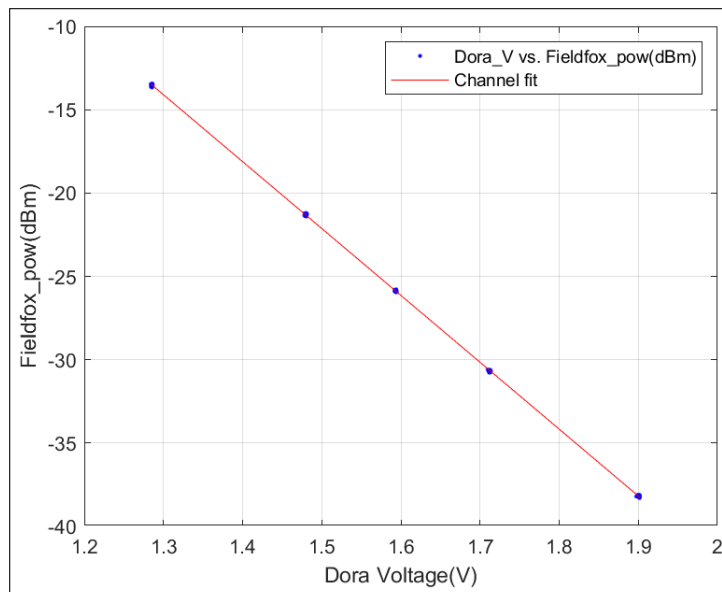


Fig. 23. Channel 7 polynomial fit plot

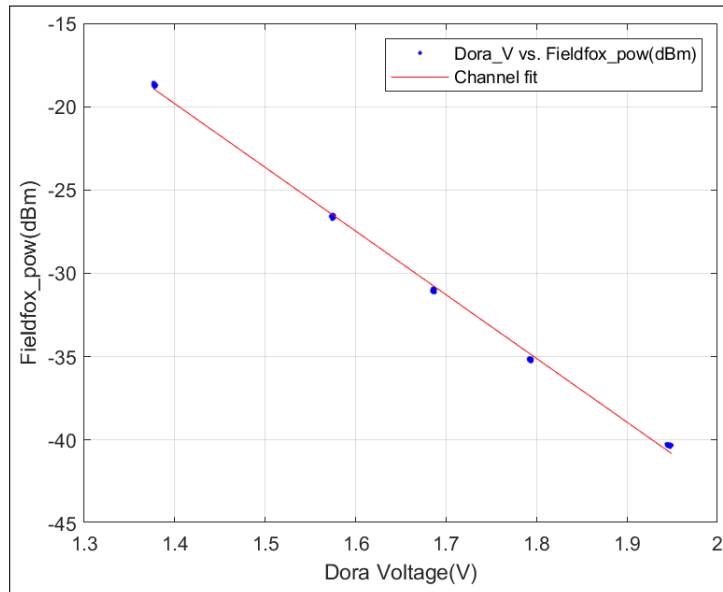


Fig. 24. Channel 8 polynomial fit plot