

EE 117B/217B Microwave and Wireless Measurements

Lab 4 - Noise and Phase Locked Loops

Fall 2026

CAUTION: READ THIS PAGE CAREFULLY BEFORE STARTING THE LAB

This class uses the FieldFox Microwave Analyzer N9918B as the primary instrument. In this lab it will be operated in its Noise Figure (NF) mode and, in several sections, its Spectrum Analyzer (SA) and Network Analyzer modes. Along with the FieldFox, this class also uses a Keysight 346C precision coaxial noise source, an evaluation board containing a VCO and a PLL, and several other RF instruments and devices under test (DUTs). Please handle the instruments very carefully as they are **very expensive** and delicate. The most vulnerable parts of the instruments are the RF PORTS (APC-3.5 connectors). These connectors are protected by the small Female-Female Port Savers, which are the silver ferrules attached to the ports. **DO NOT REMOVE THE PORT SAVERS FROM THE FIELDFOX PORTS FOR ANY EXPERIMENT.**

All connections are to be made through these Port Saver Connectors. If you have never handled RF instrumentation before, ask the instructor to demonstrate how to make connections and handle these connectors and cables. Always hold the cable with one hand (non-dominant) and rotate the end nuts of the SMA cables with the other (dominant) hand. Once you make a soft connection by hand, use the torque wrench provided to complete the connection. Note that whenever SMA connections are made, you must only rotate the end nuts and not the components; this ensures the internal pin enters and exits the jack in a straight trajectory. As far as pushing the control knobs and keys on the instrument are concerned, no special care is needed (they are fail-safe). The worst that can happen is that the instrument may lock up. In that case, press the **Preset** key or ask the instructor for help.

Caution for this particular lab

The Keysight 346C noise source is powered directly by the FieldFox's "Noise Source Drive +28 V Pulse" output. Never apply an external DC supply to the noise source, and never exceed the noise source's rated drive voltage. The noise source diode is a delicate component — do not drop the noise source or subject its output connector to lateral force when mating cables. Also, be careful when setting the DC voltages for the amplifiers.

Later in this lab you will connect DC power supplies to the VCO/PLL evaluation board. Never apply more than 13 V to the VTUNE port, check the voltage and polarity of every supply (and set the current limit) before connecting it, and make sure that no DC supply is ever connected to the RF INPUT port of the FieldFox (Port 2). NEVER APPLY MORE THAN +20 dBm OR ANY DC VOLTAGE TO THE RF INPUT PORT OF THE FIELDFOX.

Introduction

Every receiver adds noise to the signals propagating through it, degrading the signal-to-noise ratio (SNR) between its input and its output. The *noise figure* (NF) of a component or system quantifies exactly how much SNR degradation is introduced. Noise figure is one of the most important figures of merit in RF and microwave engineering: it sets the sensitivity floor of every radar, radio, and communication receiver, and it is the single number that a designer must control, stage by stage, to hit a system-level sensitivity target. In the first part of this lab you will learn how to measure noise figure using two complementary techniques: (1) the *Y-factor method* with a calibrated, electronically switched noise source, as implemented in the FieldFox's dedicated NF mode; and (2) the *gain method* (also called the *direct noise measurement method*), the simplest — and least sensitive — technique, which infers noise figure directly from a single output noise power reading and the DUT's gain. Both are cross-checked against the cascaded noise figure predicted by the Friis formula. The theory behind these methods is collected in Appendices A–C.

In the second part of the lab you will use the FieldFox in SA mode to study a voltage-controlled oscillator (VCO) and a phase-locked loop (PLL). Using the **Analog Devices EV-ADF4159EB1Z** evaluation board, you will first characterize the free-running VCO (tuning range, K_{VCO} , frequency instability and phase noise), then close the loop and measure the hold-in range, pull-in range, lock-in range, lock time and cycle slipping of the PLL, and finally compare the phase noise of the locked PLL to that of the free-running VCO. The definitions of the loop parameters and the phase noise calculation are collected in Appendix D.

Objectives

At the end of this lab you will:

1. Understand the Y-factor method and the meaning of Excess Noise Ratio (ENR).
2. Operate the FieldFox NF mode with the Keysight 346C noise source to calibrate a receiver and measure the noise figure and gain of a DUT.
3. Extend a noise figure measurement to higher frequencies and understand how ENR and instrument noise figure vary with frequency.
4. Understand and apply the Friis cascade formula for the noise figure of cascaded (multi-stage) systems, and verify it by measuring cascades of attenuator, amplifier and filter stages.
5. Correctly use a **Noise Marker** to read out a noise power spectral density, understanding why the noise marker must correct for the Equivalent Noise Bandwidth (ENBW) of the resolution bandwidth filter (and for detector/log-amp bias), unlike an ordinary marker.
6. Measure the noise figure of an amplifier chain using the gain (direct noise measurement) method, compare the result against the Y-factor measurement and the Friis formula, and understand the limitations of the method.
7. Characterize the tuning range and gain (K_{VCO}) of a VCO and observe its free-running frequency instability.
8. Measure the phase noise of a VCO and of a PLL with a spectrum analyzer and noise marker.

9. Measure the hold-in range, pull-in range, lock-in range and lock time of a PLL, and observe loss of lock and cycle slipping.

Since students are performing the lab together, please ensure that you **take turns performing the experiments**. This lab is divided into three parts: (1) Noise Figure Experiments, (2) VCO and PLL Experiments, and (3) PLL Phase Noise.

Equipment List

Table 1 lists the instruments, sources, components, and devices under test used throughout this lab. Verify that all items are present at your bench and in your Lab Box before beginning, and consult the instructor if anything is missing or damaged. Start by reading the datasheets and user guides of the components (in particular the amplifier, the noise source, the bandpass filter, and the VCO and PLL evaluation board listed in Appendix E); you will need their specifications and maximum ratings throughout the lab.

Lab Report

Each lab comes with a Lab Questionnaire. As you go through this Lab Manual, you will encounter several questions along the way. When you do, go over to that question in the Lab Questionnaire and answer it accordingly. The list of questions and answers will be turned in as your Lab Report. All students in one lab group will submit one combined lab report. **It is recommended that you complete the post-processing parts of the lab also during the designated lab hours so you can work together with your team.**

Equipment	Part Number	Qty
Keysight FieldFox Microwave Analyzer (VNA / SA / NF modes)	N9918B	1
Keysight precision coaxial noise source	346C	1
SMA coaxial cables	NA	2–3
RF amplifier (preamplifier / gain stage)	ZX60-123LN-S+	2 (1 shared)
DC bias power supply	Agilent E3631A	1
10-dB attenuator (DUT)	FW-10A+	1
Bandpass filter (narrow-band stage)	VBFZ-5500-S+	1
50 Ω matched load / SMA termination	NA	2
Male-Male / Female-Female SMA adapters	NA	2 each
VCO / PLL evaluation board (ADF4159 + HMC515LP5E VCO)	EV-ADF4159EB1Z	1
DC power supplies for the evaluation board (5.5 V and 15 V)	NA	2
Oscilloscope	NA	1
PC workstation with ADF4158-9 evaluation software and USB cable	NA	1
SMB-to-BNC cable (noise source drive), SMA-to-BNC cable	NA	1 each
Banana-to-SMA adapter and banana-to-test-hook cables	NA	1 set
Torque wrench	(shared)	1
USB flash drive	Sandisk	1

Table 1: Equipment used in the Noise and Phase Locked Loops Lab 4 experiments.

1 Noise Figure Experiments

This class uses the FieldFox’s built-in **NF mode** together with a **Keysight 346C** calibrated, electronically switched (“hot/cold”) noise source to make Y-factor noise figure measurements. Unlike the older bench noise figure meters (which pair a dedicated NFM instrument with an external noise source and, optionally, an external spectrum/signal analyzer), the FieldFox is a single all-in-one instrument: switching it into NF mode turns it into a calibrated noise receiver that drives the 346C directly from its own “Noise Source Drive +28 V Pulse” port, reads the resulting hot/cold power levels, and computes noise figure and gain internally. The Y-factor method, the Excess Noise Ratio (ENR) and the Friis cascade formula are explained in Appendices A and B.

1.1 Calibrating the FieldFox NF Mode

1. Connect the 346C noise source to the FieldFox DC output (left side panel, center pin) using the SMB to BNC cable. Connect the Noise Source RF output directly to FieldFox Port 2 with an SMA cable and a F-F adapter.

2. Turn on the FieldFox and select NF mode:

Mode → **NF**

3. Set the frequency range for this first experiment:

Freq → **Start** → 10 MHz

→ **Stop** → 18 GHz

Sweep → **Points** → 51

4. Enter the ENR table for your specific 346C. Read the ENR values off the calibration sticker on the back of the Noise Source. If a table already exists, make a new one. Make sure to add the ENR values for all frequencies listed.

Meas Setup → **Noise Source** → **ENR Table Edit/Save/Recall** → **Edit ENR Table**

5. Use knob and press **Edit** to make changes. Press **Done** to exit.
6. Make sure the noise source is connected directly to the FieldFox, so we can now calibrate the instrument itself. Run the calibration:

Cal → **Run Receiver Cal** → **Measure**

The FieldFox will pulse the noise source on and off at every frequency point and store $F_{\text{rec}}(f)$ and $G_{\text{rec}}(f)$ (here $G_{\text{rec}} \approx 0$ dB since it is being measured against itself).

7. Click **Done** once finished and autoscale to observe the calibrated Noise Figure.
8. If the screen is not updating and **Hold** is on (see top left corner of screen, it should be in red color), click **Run/Hold** to measure the NF.

Record the receiver’s own calibrated noise figure at 100 MHz and 1000 MHz (**Q1.1.1**). This is the noise figure the FieldFox will subtract out (via the cascade formula) from every subsequent DUT measurement. It should be around 0. Why is it not exactly zero (**Q1.1.2**)? Plot the resulting display (**Q1.1.3**).

1.2 Measuring a DUT

1. Insert the 10 dB attenuator between the noise source and Port 2. Click **Run/Hold** and rescale as needed. Is the NF as expected for an attenuator? Save (as a CSV file) and plot the resulting NF over frequency (**Q1.2.1**).
2. Replace the 10 dB attenuator with the RF Amplifier. **Bias the amplifier carefully (check the datasheet and set a current limit)**. Repeat the NF measurement and display the corrected noise figure and gain traces:

Meas → Noise Figure Meas → Gain

3. Save the Noise Figure and Gain traces (as CSV files) and plot them. Compare your results with the datasheet (**Q1.2.2**). Turn off the DC supply to the Amplifier.
4. To measure the Amplifier gain using S-parameters we will run a simpler calibration procedure. Connect two SMA cables to the two ports of the FF and connect the other ends to each other using a F-F adapter. Then run a Response Cal as follows:

Cal → Response Cal → Normalization → Measure

Then replace the F-F adapter with the RF Amplifier and measure the gain from S21. Plot and compare this gain with the gain obtained from the NF measurements (**Q1.2.3**).

5. From the gain and the noise figure, compute and plot the Noise Measure of this amplifier over the frequency range (**Q1.2.4**).
6. Lastly, measure the noise figure and gain of the Band Pass Filter (4.9 GHz - 6.2 GHz) over the same frequency range. Save and plot the results (**Q1.2.5**).

Reminder: Take turns in doing the experiments.

1.3 Noise Figure of Cascaded Stages

1. Cascade the 10 dB Attenuator followed by the RF Amplifier and measure the Noise Figure. Then connect the Amplifier followed by the attenuator and measure the Noise Figure. Plot and compare the two results. Comment on the differences (**Q1.3.1**).
2. Compute the Noise Figure of these two cases from Friis's equation for cascaded noise figure (Appendix B). Do the results agree with the measurements you made directly? Plot the comparison (**Q1.3.2**).
3. Add the BPF to the cascade. You should have the BPF first, the Amplifier next and the attenuator last. Measure the noise figure of this cascade and compare with the computed value from the cascaded NF formula (**Q1.3.3**).
4. Given that the linear response of the three stages would remain the same for any order that they are placed, which order would you use if you want to minimize the NF over the entire band (10 MHz to 18 GHz)? Connect it in this order and measure the NF over the band. Compare it with the result computed using Friis's equation (**Q1.3.4**).
5. If the results don't agree with what you computed, check the measurement uncertainty:

Meas Setup → Uncertainty → Uncert Bars

Comment on whether your computed results lie within the uncertainty bars of the measurement (**Q1.3.5**).

Reminder: Take turns in doing the experiments.

1.4 Computing the Noise Figure Using the Gain Method

Next we will measure the Noise Figure without the use of the Noise Source. Although this method is simple to implement, it has its limitations, which we will explore. Refer to Appendix C for a brief overview of the gain method.

1. Set up the FieldFox in the Spectrum Analyzer mode (SA). Connect the RF amplifier output to Port 2 of the FF using an SMA cable. Connect a 50 Ohm matched load to the input of the Amplifier. Connect up the DC cables, check the current limit and turn on the Amplifier.
2. Set the SA to the following settings:

Freq/Dist → Center → 10 GHz
→ Span → 10 MHz
BW → Res BW → 1 kHz
→ Video BW → 100 Hz

Set RF attenuation to 0 dB. The marker value now reads the noise power through the IF Filter of 1 kHz. Is the Equivalent Noise Bandwidth also 1 kHz (**Q1.4.1**)?

3. In order to read the noise power spectral density, we will use a noise marker.

Marker → More → Marker Function → Noise

What value do you read on the Marker now? Can you explain what this value represents (**Q1.4.2**)?

4. Now turn on the Amplifier. Did the marker reading change? If not, why not? What do you expect the output noise power to be from the amplifier (**Q1.4.3**)?
5. Disconnect the amplifier from Port 2 and terminate Port 2 with the 50 Ohm matched load. What is the noise power spectral density now? How does it compare to what you measured earlier? What is the Noise Figure of the Spectrum Analyzer itself? Based on this can you explain why the Gain method would fail to measure the Noise Figure of this amplifier (**Q1.4.4**)? Turn off the DC Power Supply to the Amplifier before proceeding.
6. Next we will try this method with two cascaded Amplifier stages. First we need to measure the gain of the two amplifiers. Go to VNA Mode on the FF and perform a Response Cal with two SMA cables connected to the two ports with a F-F adapter between them.
7. Next borrow another RF Amplifier from your neighboring station and connect the two amplifiers in a cascade. **CAUTION: MAKE SURE THE VNA POWER IS SET TO -30 dBm.**

Meas Setup → Power Level -30 dBm

This is to ensure that the output power from the first stage does not saturate the second stage and also the total output power does not exceed the VNA port limits. Adjust the current limit on the power supplies to handle both amplifiers.

8. Once you are sure that the DC and RF connections are good and the VNA port power level is set to -30 dBm, turn on the power supplies and measure the gain of the cascade at 10 GHz (**Q1.4.5**).
9. Turn off the DC Power Supplies, disconnect the input SMA cable and replace it with the 50 Ohm termination. Switch to the SA Mode and use the same settings as earlier. What does the Noise Marker at 10 GHz read now? Do you see the marker value change when the DC supplies are turned on and off (**Q1.4.6**)?
10. Using the Gain and the Noise Power at the output calculate the Noise Figure at 10 GHz using the Gain Method. Does this result agree with the cascaded noise figure calculation for two amplifiers (**Q1.4.7**)?
11. Turn off the power supply and disconnect the setup. Ask the instructor for help in disconnecting the SMB-BNC cable.

Reminder: Take turns in doing the experiments.

2 VCO and PLL Experiments

Until now you used the spectrum analyzer to characterize passive and active components. In this part of the lab, we use the SA to measure a phase-locked loop (PLL). We will be using the **Analog Devices EV-ADF4159EB1Z** evaluation board. The evaluation board integrates a complete PLL: the **ADF4159** synthesizer chip (phase-frequency detector, charge pump, and programmable dividers), an active loop filter with **OP-184** op-amp, and an **HMC515LP5E** VCO tuning from 11.5 - 12.5 GHz. A 100 MHz temperature-compensated crystal oscillator (TCXO) on the board provides the reference. The board feeds the VCO output *divided by two* back to the ADF4159, so when the VCO runs at 12 GHz, the signal at the RF input of the ADF4159 is at 6 GHz. The phase-frequency detector itself compares at a much lower rate derived from the 100 MHz reference. The full-rate VCO signal is available at the **EXT_VCOOUT** SMA connector, and the control voltage is available at the **VTUNE** SMA connector. The FieldFox measures signals directly up to 26.5 GHz, so it can observe the VCO output without an external mixer.

The board is programmed over USB from a PC running the Analog Devices ADF4158-9 evaluation board software. You can either use your own laptop or the PC connected to your station. If the PC does not already have the Evaluation Board software you can download and install it from the Analog Devices website (see the ADF4158-9 software and EVAL-ADF4159 product page links in Appendix E).

Read through the installation guide (UG-476, Appendix E) to install the software. The software details are in the UG-383 user guide (Appendix E), **which you should read through before starting the lab**. Also read through the datasheet of the VCO (HMC515LP5, Appendix E).

2.1 DC Characterization of the VCO

In this experiment we want to characterize the VCO tuning range and K_{VCO} which is the slope of the VCO frequency to the tuning voltage. We break the loop's control of the VCO by driving the

tuning line directly from a DC power supply and reading the resulting frequency on the spectrum analyzer.

1. Connect the 5.5 V supply to the banana jack connectors. Check the DC voltage, polarity and set an appropriate current limit (0.5 A). Terminate the VCO/2 port with a 50 Ohm load. Connect the EXT_VCOOUT to the SA input Port (PORT 2). In order to tune the VCO directly, connect the 15 V DC power supply output to the VTUNE SMA port (you will need a banana to SMA connector). Start the VTUNE voltage at 6 V. Check the power supply values and the current limits. Turn on the supplies. Check that the 5.5 V, which drives the VCO, is drawing the right amount of DC current (see datasheet).
2. On the FieldFox, select SA mode. Set the center frequency to 11.5 GHz, the span to 3 GHz. Choose the right RBW and number of points accordingly. You can use Signal Track if you want to.
3. Vary V_{tune} across the full usable range (2 V - 13 V) in steps of 0.5 V, and at each step record the applied voltage and the marker frequency. **Do not exceed 13 V.** If the peak leaves the screen, widen the span or re-center. Record and plot the data (f_{VCO} vs V_TUNE) (Q2.1.1). Report the tuning range (minimum and maximum frequency, and the total span in GHz) over the usable tuning-voltage range (Q2.1.2).
4. From the slope of the curve, compute K_{VCO} as a function of tuning voltage. Is the VCO gain constant across the tuning range, or does it vary (Q2.1.3)? Report the average K_{VCO} and compare your value with the value reported in the User Guide (UG-383) ($K_{\text{VCO}} = 150$ MHz/V at the VCO output). Note that the loop sees VCO/2, so the effective gain at the phase detector is half the value you measure at EXT_VCOOUT — state clearly which frequency your reported K_{VCO} refers to (Q2.1.4).
5. Set V_TUNE to 6 V. The frequency you read on the spectrum analyzer fluctuates from sweep to sweep. To observe this you need to center the peak, reduce the span (10 MHz) and RBW (1 kHz). Turn on Signal Track and observe the marker frequency over time.
6. Next turn Signal Track OFF and use the Max Hold option to visualize the frequency drift. Why is the center frequency trace becoming wider with time? After waiting a few minutes report the width of the center frequency trace (Q2.1.5). Turn off Max Hold.
7. Note the approximate peak-to-peak frequency variation. This is the free-running frequency instability of the VCO — part residual FM (jitter), part slow drift. We will quantify the phase noise later in this lab (Sections 2.2 and 3) (Q2.1.6). Bring your finger close to the VCO and hover over it at a close distance (1 mm). Do you see the frequency change? Can you explain why the frequency changes despite not touching the VCO (Q2.1.7)? What happens if you gently touch it? Why does the frequency always decrease when hovering or touching the VCO (Q2.1.8)?

Reminder: Take turns in doing the experiments.

2.2 VCO Phase Noise

Next we will attempt to measure the Phase Noise of the VCO with the Spectrum Analyzer. The relation between the measured noise spectral density and the phase noise is given in Appendix D.

1. Center the frequency and reduce the span to 1 GHz. Reduce the RBW to 10 kHz. Note down the peak signal power. Reduce the span to 10 MHz and the RBW to 100 Hz. What is the peak signal power now? Why did it drop (**Q2.2.1**)?
2. Next use the noise marker to measure the noise spectral density (you will learn more about this during the noise figure part of this lab; see Appendix C):

Marker → More → Marker Function → Noise

3. Measure the noise spectral density at 10 kHz, 100 kHz and 1 MHz offsets from the peak frequency. You can use the Run/Hold command to fix the trace (**Q2.2.2**).
4. Based on the signal peak power and the measured noise spectral densities report the Phase Noise of the VCO at these offset frequencies in dBc/Hz (**Q2.2.3**).

Reminder: Take turns in doing the experiments.

2.3 Hold-In Range and Lock Time

1. Turn off the power supply. Set the SA span to 10 - 13 GHz. Next, we start investigating the PLL operation. Disconnect the VTUNE from the 15 V supply. Connect the 15 V supply to the OP AMP via the test loops using banana to test hook DC cables that are labeled +15V and AGND1. Turn on the power supplies (5.5 V and 15 V) and check the current consumption (around 150 mA on 5.5 V and around 1 mA on the 15 V). Make sure the VCO/2 SMA port is terminated in 50 Ohm. Then connect to the PLL board through the PLL software. Ensure that the LEDs on the board (red and green) are ON. Make sure in the software on the bottom left it says “Analog Devices RFG.L Eval Board connected” in green.
2. Program the chip to lock the VCO at a nominal frequency of 12 GHz following the User Guide (UG-383). Note that the VCO Output Frequency in the software must be set to 6000 MHz, in order to generate an output frequency of 12 GHz (see the $\text{RFout} \times 2$ (MHz) value on the software panel). Leave the rest of the settings default. Click Write All Registers. Measure the EXT_VCOOUT signal on the SA by connecting it to Port 2 using an SMA cable. Center the peak, set the span to 1 MHz and the RBW to 1 kHz. Is the signal stable now? What happens when you bring your finger close to the VCO this time (**Q2.3.1**)?
3. Measure VTUNE signal (VCO control voltage) using an oscilloscope. Use an SMA to BNC cable to connect VTUNE from the board to the scope. Set the scale and trigger to capture the VTUNE signal. What is the VTUNE voltage at 12 GHz output? Change the VCO Output Frequency on the Software and note the change to VTUNE. Does this match your expectations from the K_{VCO} you measured earlier? Check and report the VTUNE values at 11 GHz, 11.5 GHz, 12 GHz and 12.5 GHz. Plot these results on your earlier VTUNE vs VCO frequency plot (**Q2.3.2**).

Next, we characterize three properties of the loop: how far the loop can be pushed before it loses lock (the hold-in range), frequencies over which it can acquire lock (pull-in range), and frequencies over which it can acquire lock without cycle slipping (lock-in range). These terms are defined in Appendix D.

Hold-In Range

1. Start from the locked condition at any frequency, and increase the output frequency in steps of 5 MHz (on the software panel). To do this set the **VCO Output Frequency** in the Software (note that this is half the actual PLL output frequency). After each step, confirm on the spectrum analyzer that the loop is still locked (clean line at the new frequency). You can use the signal track feature with appropriate Span and RBW. Continue until the loop can no longer lock. At the point of lock failure, record and plot the spectrum of the signal. Can you explain why the spectrum looks like this? Look at the VTUNE signal, what do you see (**Q2.3.3**)?
2. Once you find the frequency at which the PLL lock fails, increase the VCO Output Frequency by one more step of 5 MHz. Now what does the spectrum look like? Record and plot the spectrum. Is the PLL Locked? If yes, how come it is locked at a frequency higher than before? If not, why is the spectrum now so much cleaner? Look at the VTUNE signal, what do you see (**Q2.3.4**)?
3. Keep increasing the VCO Output Frequency in steps of 20 MHz. The VCO is now in open loop and the center frequency does not increase. However, you will start to see spurs in the spectrum. Record and plot the trace. Also explain why these spurs exist (**Q2.3.5**).
4. Lower the frequency back until you are just higher than the frequency at which you lost the lock. One more 5 MHz step down should be within your Hold In range. Try reducing the frequency down by 5 MHz. What happens to the spectrum? Plot the spectrum and plot the VTUNE signal. Can you explain why you are unable to lock the PLL although you are at a frequency where it was locked earlier (**Q2.3.6**)?
5. Now repeat the experiment starting from a locked frequency and decreasing by steps of 5 MHz. Report your results. What is the Hold-In Range (**Q2.3.7**)?
6. Try reaching the ends of the Hold-In Range with steps of 1 MHz (in the software). Do you see a difference in the measured Hold-In Range now? Report your final Hold-in Range. Note that the range you report should be the actual output frequency range, not what is displayed in the software **VCO Output Frequency** (**Q2.3.8**).

Reminder: Take turns in doing the experiments.

Pull-In Range and Cycle Slipping

7. Set the frequency above the maximum Hold-In range. Lower the frequency in steps of 1 MHz (in the software). Record the frequency at which the loop acquires lock. This is the upper limit of the Pull-in range. Repeat the same for the lower limit and report the final Pull-in range. Note that the range you report should be the actual output frequency range, not what is displayed in the software **VCO Output Frequency** (**Q2.3.9**).

Lock-in Range

8. Set the **VCO Output Frequency** to 12 GHz. Set the scope to trigger on a change in V_{tune} (single-shot trigger). Command a frequency step by changing the **VCO Output Frequency** by 10 MHz. Capture the V_{tune} transient as the loop acquires the new frequency. This

requires proper settings on the Trigger signal (figure out this part yourself; only ask the TA after doing your due diligence). Record the Oscilloscope output. What is the settling time or lock time? This is the time it takes for the VTUNE signal to reach 90% of the final state (**Q2.3.10**).

9. **Cycle slipping.** Start by setting the VCO Output Frequency to 6000 MHz. Make a *large* frequency step by increasing the VCO Output Frequency **by 100 MHz**. Record the Oscilloscope output. Do you see cycle slipping? Explain why this happens. What happens if you take a step of 200 MHz starting from 6000 MHz? Record the Oscilloscope output and compare with the 100 MHz step case (**Q2.3.11**).
10. To calculate the lock-in range, start from 6000 MHz and add progressively larger steps (1 MHz, 2 MHz, etc.) until you start to see cycle slipping. Each time you want to increase the step size, go back to 6000 MHz and then take a step. Record the highest frequency before you start to see a cycle slip. Do the same for the lower frequency end. This gives you the lock-in range. Report the range (once again at the actual output frequency of the PLL) (**Q2.3.12**).

Reminder: Take turns in doing the experiments.

3 PLL Phase Noise

Next we measure the Phase Noise of the PLL and compare it to the VCO.

1. Set the center frequency to 12 GHz. On the SA, set the frequency to 12 GHz and reduce the span to 10 MHz. Set the RBW to 10 kHz. Note that the center frequency of the PLL is not exactly 12 GHz, why (**Q3.1**)? Note down the peak signal power. Center the peak frequency and reduce the span to 1 MHz and the RBW to 100 Hz. What is the peak signal power now? Why did it **not** drop this time, as opposed to the free running VCO case (**Q3.2**)?
2. Next use the noise marker to measure the noise spectral density:

Marker → More → Marker Function → Noise

3. Set the appropriate span and RBW. Measure the noise spectral density at 10 kHz, 100 kHz and 1 MHz offsets from the peak frequency. You can use the Run/Hold command to fix the trace (**Q3.3**).
4. Based on the signal peak power and the measured noise spectral densities report the Phase Noise of the PLL at these offset frequencies in dBc/Hz (**Q3.4**). Compare it with the phase noise of the free-running VCO from Q2.2.3 at the same offsets (**Q3.5**).

Congratulations! You have completed the lab. Please power down all the instruments, and return all components safely to the box just as you received them. Get checked off by the instructor before you leave.

Appendix

A The Y-Factor Method

The noise source has two states. In the “off” (cold) state its output is simply a $50\ \Omega$ termination at (approximately) the ambient physical temperature $T_0 = 290\ \text{K}$. In the “on” (hot) state, an internal breakdown diode injects excess noise, so that the source behaves like a resistor at an elevated noise temperature T_h . The *Excess Noise Ratio* (ENR) of the source, in dB, is defined as

$$\text{ENR} = 10 \log_{10} \left(\frac{T_h - T_0}{T_0} \right),$$

and is supplied by the manufacturer as a table of values versus frequency on a calibration sticker/report for the specific 346C serial number you are issued. When the noise source is connected to the input of a receiver of gain G and noise factor F_{rec} and switched on and off, the receiver output power is measured in both states, N_{on} and N_{off} . Their ratio is the *Y-factor*:

$$Y = \frac{N_{\text{on}}}{N_{\text{off}}}.$$

It can be shown that the noise factor of the receiver is

$$F_{\text{rec}} = \frac{\text{ENR}_{(\text{linear})}}{Y - 1}, \quad \text{NF}_{\text{rec}}(\text{dB}) = 10 \log_{10} F_{\text{rec}}.$$

This is exactly the calculation the FieldFox NF mode performs internally every time you calibrate or measure. When a DUT is inserted ahead of the (now-characterized) receiver, the FieldFox repeats the Y-factor measurement for the cascade of DUT + receiver, and then uses the Friis cascade formula (Appendix B) with the previously stored receiver calibration to solve for the DUT’s own noise figure and gain – this is exactly analogous to a VNA removing the effect of its own directivity/tracking errors after a calibration.

B The Friis Cascade Formula

For a cascade of stages with linear gains $G_1, G_2, \dots$ and linear noise factors $F_1, F_2, \dots$ (noise factor $F = 10^{\text{NF}/10}$, gain $G = 10^{G(\text{dB})/10}$), the noise factor of the cascade is

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots, \quad \text{NF}_{\text{total}} = 10 \log_{10} F_{\text{total}}. \quad (1)$$

A passive attenuator with loss L (linear, $L > 1$) at the reference temperature T_0 has $F = L$ and $G = 1/L$, i.e. its noise figure in dB equals its loss in dB. The *noise measure* of a stage is

$$M = \frac{F - 1}{1 - 1/G}, \quad (2)$$

which is the quantity that Eq. (1) effectively minimizes when stages are cascaded.

C The Gain Method and the Noise Marker

Gain method. A matched $50\ \Omega$ source at $T_0 = 290\ \text{K}$ delivers a thermal noise power density of $kT_0 \approx -174\ \text{dBm/Hz}$. A DUT of gain G (dB) and noise figure NF (dB) driven by such a source therefore produces an output noise power density

$$N_{\text{out}}\ (\text{dBm/Hz}) = -174 + \text{NF} + G, \quad \text{so} \quad \text{NF} = N_{\text{out}}\ (\text{dBm/Hz}) + 174 - G.$$

Thus, if the output noise density and the gain are measured (the latter with a network analyzer), the noise figure follows from a single noise reading, without a noise source. The method is only valid if the measured noise density is dominated by the DUT. When the DUT's output noise lies below the noise floor of the analyzer, the analyzer simply displays its own noise; with a noise figure NF_{SA} for the analyzer the displayed density is at least $-174 + \text{NF}_{\text{SA}}$ dBm/Hz. The DUT must therefore have enough gain that $G + \text{NF} \gg \text{NF}_{\text{SA}}$, which is why a second amplifier is cascaded in Section 1.4.

Noise marker. The marker of a spectrum analyzer normally reads the power in the resolution-bandwidth filter, which is defined by its 3 dB bandwidth. Noise power, however, is determined by the *equivalent noise bandwidth* (ENBW) of the filter, which is slightly different from the 3 dB bandwidth. In addition, the log amplifier and envelope detector of the analyzer under-read the average power of noise-like signals by a fixed amount. The noise marker applies both corrections and normalizes the result to a 1 Hz bandwidth, so that it reads a noise power spectral density in dBm/Hz that is independent of the RBW setting.

D Phase-Locked Loop Parameters and Phase Noise

VCO gain. The VCO gain $K_{\text{VCO}} = \Delta f / \Delta V_{\text{tune}}$ (MHz/V) is the slope of the frequency versus tuning-voltage curve.

Hold-in range. The range of frequencies over which the loop, once locked, can maintain lock as the target frequency is changed. It is set by the DC loop gain and is ultimately bounded by the VCO tuning range.

Pull-in (capture) range. The range of frequencies over which the loop can acquire lock from an unlocked state.

Lock-in range. The range of frequencies over which the loop can acquire or maintain lock without *cycle slipping*, i.e. without the phase error exceeding one cycle (2π) during the transient.

Lock time. The time it takes the control voltage to settle (here to 90% of its final value) after a frequency step.

Phase noise from the noise marker. If the carrier power is P_c (dBm) and the noise power spectral density at an offset Δf from the carrier, read with the noise marker, is $N(\Delta f)$ (dBm/Hz), the single-sideband phase noise at that offset is

$$\mathcal{L}(\Delta f) = N(\Delta f) - P_c \quad [\text{dBc/Hz}]. \quad (3)$$

The result is valid only if the noise measured is the phase noise of the source and not the noise floor or the phase noise of the analyzer itself.

E References

Software

- EVAL-ADF4159 Evaluation Board Product Page and Software
- ADF4158-9 PLL Software
- ADIsimPLL PLL Design & Simulation Tool

User Guides

- UG-476: PLL Software Installation Guide
- UG-383: EVAL-ADF4159 Reference Guide

Datasheets

- ADF4159 Frequency Synthesizer Datasheet
- HMC515 VCO Datasheet
- OP184 Operational Amplifier Datasheet