ELEN90062 High Speed Electronics
Workshop Three
Vector Network Analyser (VNA) Calibration and Measurement

Welcome to Workshop 3 for High Speed Electronics. The objective of this hardware workshop is to get yourself familiarise in calibrating and using the Vector Network Analyser (VNA) when taking RF measurements.

Instructions

- The workshop is worth 5% of your final subject mark.
- You must complete the pre-lab exercise before coming to the class
- You must show the completed tasks to your workshop demonstrator.
- The report should have a brief executive summary detailing the objective of the workshop. The remaining part of the report should consist of the outcome of the tasks below (calculations, plots, discussions etc.).
- The report should clearly show the equations used in calculations.
- The report is due on 14/09/2018.
- Submit one report per group.

S-Parameters, Reflection Coefficient, and Impedance

The scattering parameters, widely known as S-parameters, are frequently used in RF signal measurements. The S-parameters express how the travelling wave currents and voltages are affected when a network is introduced to a transmission line, for example an unmatched load. Unlike the z, y, and a parameters which are defined by short or open circuiting the ports, the S-parameters are defined by terminating the lines at matched loads at each port.
In the 2-port network shown in Figure 1, the incident waves, the waves coming into the 2-port network, are defined as a_1 and a_2 while the reflected waves at each port are defined as b_1 and b_2. When $Z = 0$ and $Z_G = Z_L$, we have a matched load and therefore maximum power transfer at the load with $V_1 = V_2 = V_g/2$.
The relationship between S-parameters and incident and reflected waves are defined as follows:

$$b_1 = S_{11}a_1 + S_{12}a_2 \qquad b_2 = S_{21}a_1 + S_{22}a_2 \tag{1}$$

$$S_{11} = \frac{b_1}{a_1}|_{a_2=0} \qquad S_{12} = \frac{b_1}{a_2}|_{a_1=0} \qquad S_{21} = \frac{b_2}{a_1}|_{a_2=0} \qquad S_{22} = \frac{b_2}{a_2}|_{a_1=0} \tag{2}$$

The physical meaning of S_{11} is the input reflection coefficient with the output of the network terminated by a matched load ($a_2 = 0$). S_{21} is the forward transmission (from port 1 to port 2), S_{12} the reverse transmission (from port 2 to port 1), and S_{22} the output reflection coefficient.
Using incident waves as positive and reflected waves as negative, it could be easily shown that a_i and b_i satisfy the following equations.

$$a_i = \frac{V_i + I_iZ_0}{2\sqrt{Z_0}} \qquad b_i = \frac{V_i - I_iZ_0}{2\sqrt{Z_0}} \tag{3}$$

Where Z_0 is the reference impedance, usually taken as 50Ω.

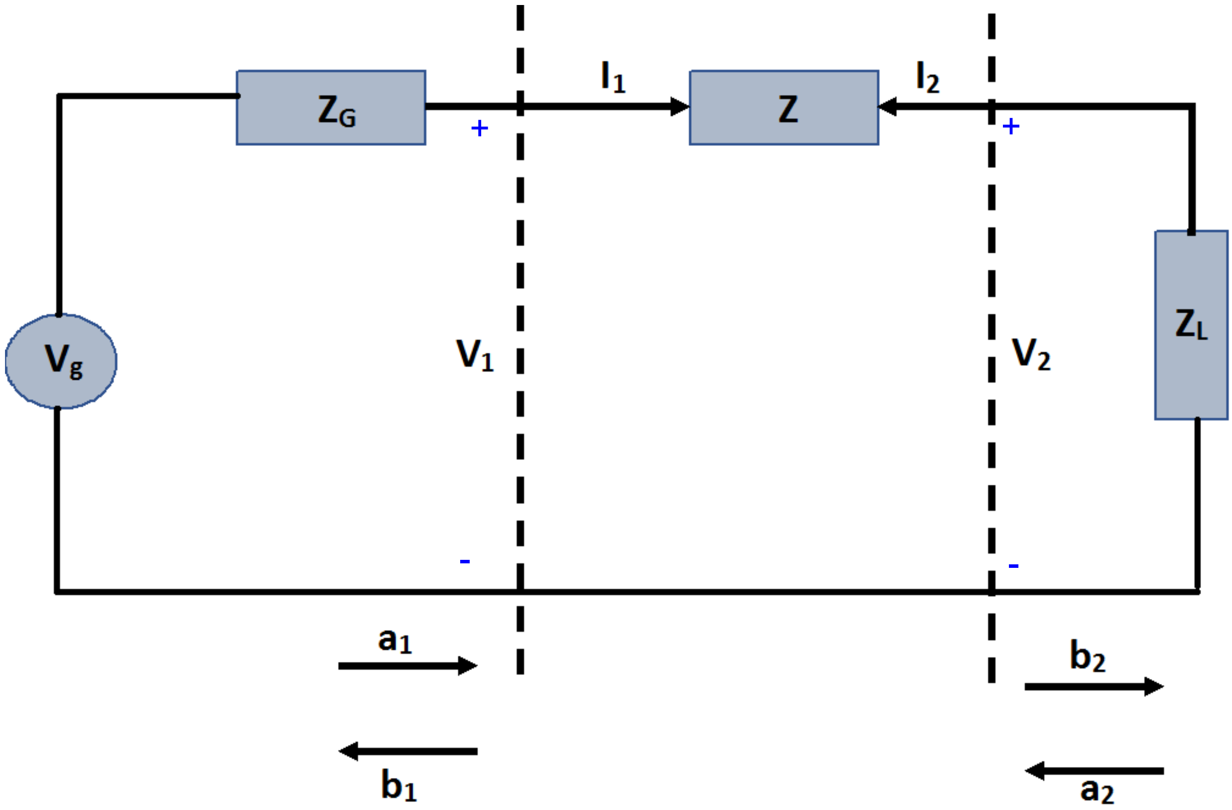

Figure 1: Two port network

Task 1: Consider a 2-port network as shown in Figure 1 where $Z_G = Z_0$ and $Z = 0$. Using equations (2) and (3), prove;

$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{4}$$

Task 2: Now consider a 2-port network as shown in Figure 1 where $Z_G = Z_L = Z_0$ and $Z \neq 0$. Using equations (2) and (3), prove;

$$S_{21} = \frac{2Z_0}{Z + 2Z_0} \tag{5}$$

In the first stage of this workshop, you will calibrate the VNA using Short, Open, Load, and Through (SOLT) calibration circuit board. You will then use the calibrated VNA to take S-parameter measurements of unknown shunt and series impedances. Finally, using equations (4) and (5), you will calculate the unknown shunt and series impedances.

Calibrating the Vector Network Analyser

The vector network analyser (VNA) is a frequently used equipment in RF electronics, specially in taking S-parameter measurements and Smith charts. Before using the VNA for RF measurements, it is important that we calibrate the equipment. Lets find out why?

Consider the RF circuit shown in Figure 2. The objective of the experimental set up shown in Figure 2 is to measure the impedance or the power of the amplifier shown in the circuit. However, at high frequencies, many external factors such as impedances of unknown cable lengths and impedance at the connectors affect our measurements. The objective of calibrating the VNA is to isolate the circuit of interest from these external factors and set a measurement point. For this purpose, we use a set of empty fixtures to calibrate out these effects as shown in Figure 3. Figure 4 illustrates the short, open, load, and through circuits in detail.

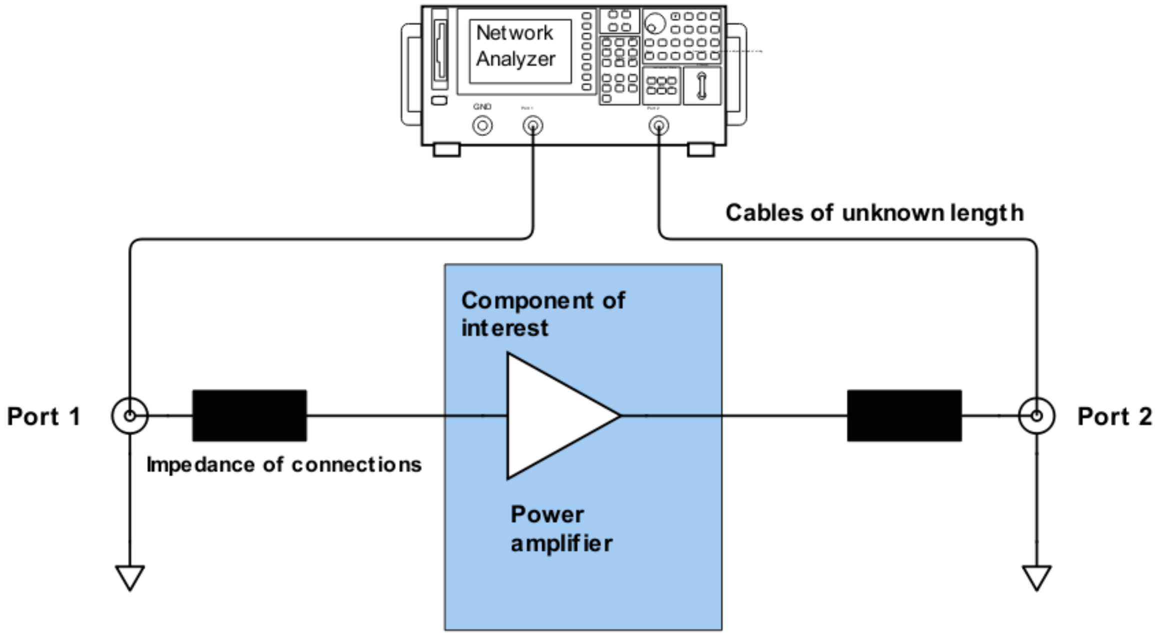

Figure 2: RF Circuit Measurements Using VNA

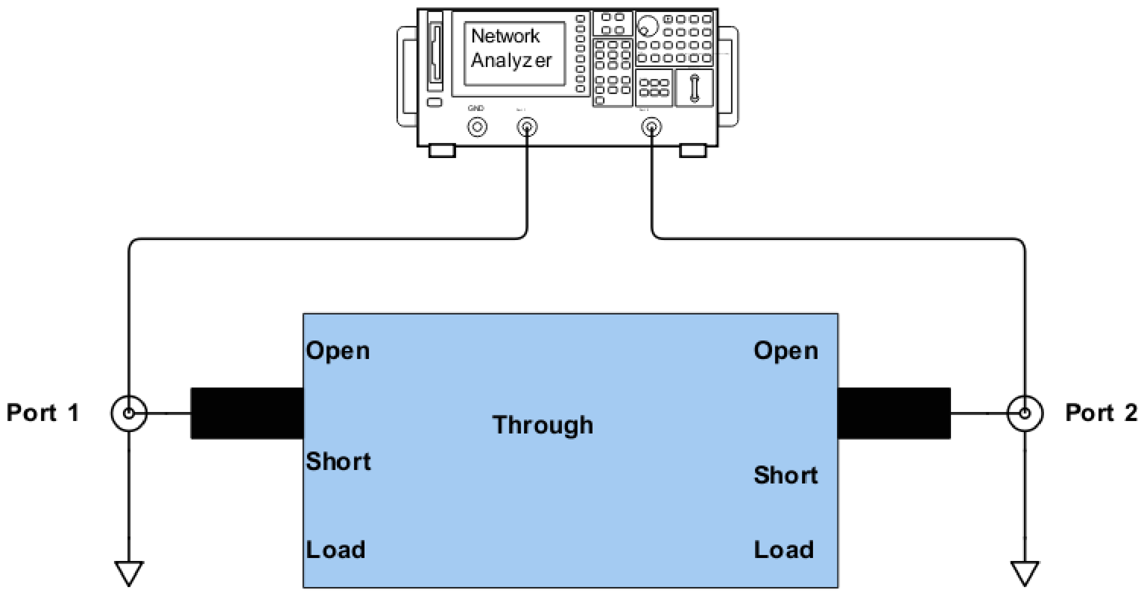

Figure 3: Vector Network Analyser Calibration

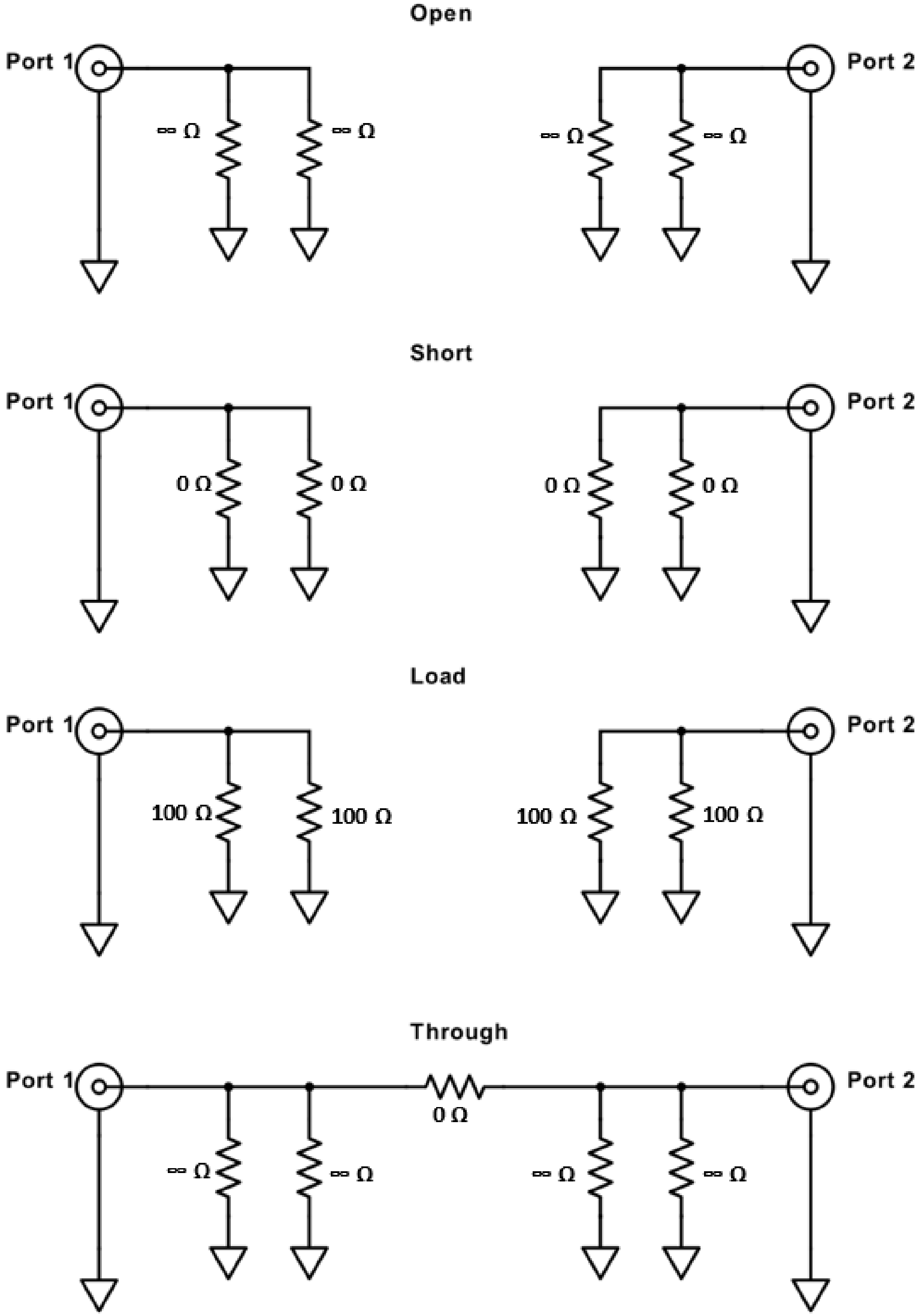

Figure 4: Open, Short, Load, and Through Circuits

VNA Calibration Steps

Figure 5 illustrates the VNA and the SMA-SMA cable used in connecting RF circuits to the VNA. Figure 6 shows the SOLT calibration circuit board and the unknown impedance circuit board.

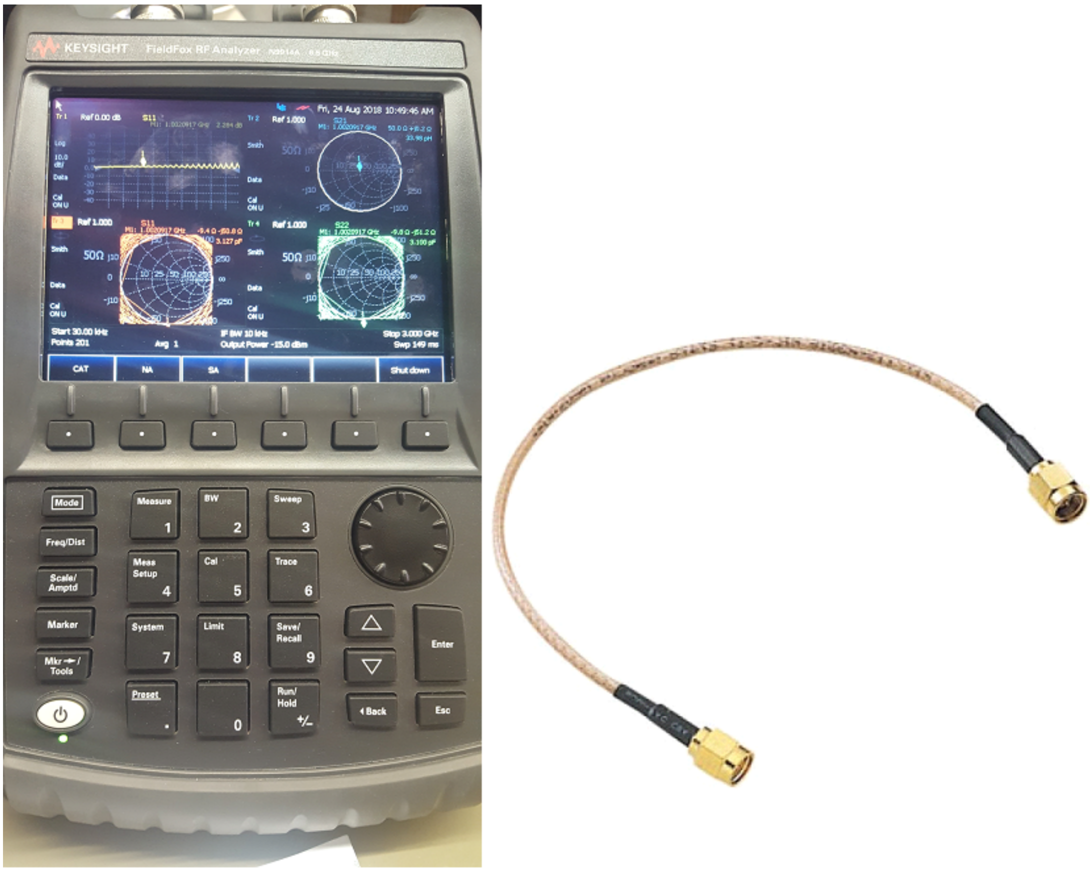

Figure 5: Vector Network Analyser and SMA-SMA cable

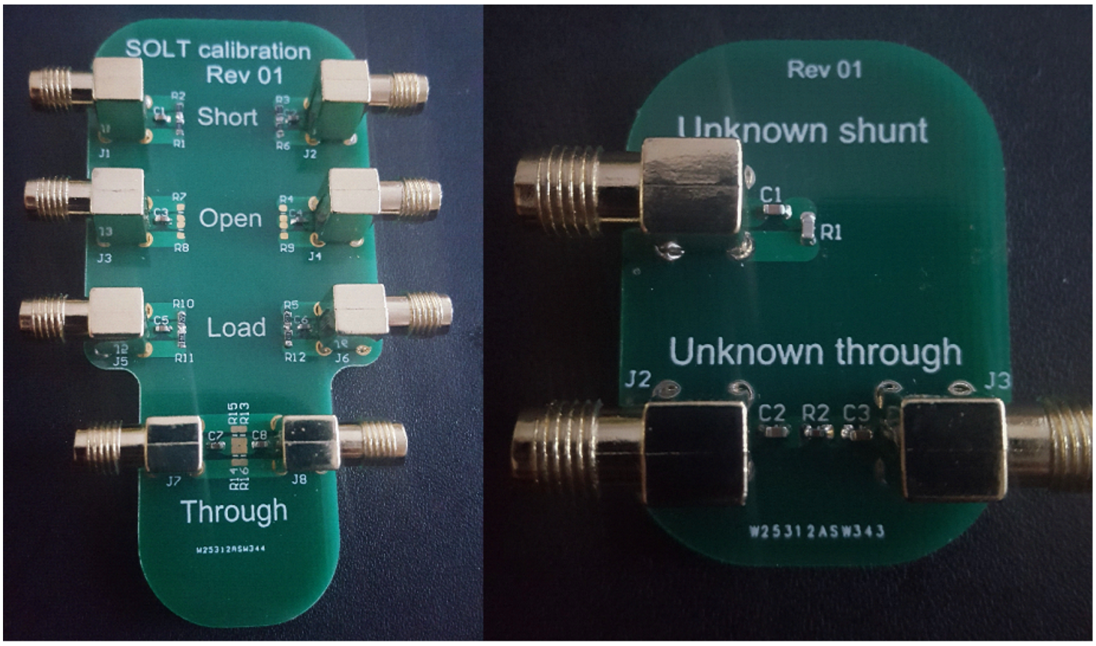

Figure 6: SLOT calibration and unknown impedance circuits

1. Power ON the VNA and connect the SMA-SMA cables to port 1 and 2 of the VNA.
2. Preset → Preset
3. Mode → NA
4. Setting the number of traces. We set the number of traces to 4 as we want to observe the four S-parameters.
   Trace → Num of traces → x4H
5. Setting the operating frequency range
   Freq/Dist → Start → 100.00 MHz → Stop → 3 GHz.
6. Calibration process
   Cal → Mechanical Cal → Change cal type → Full 2-port → Back
   Change DUT connectors - Use the up and down keys on the VNA to select a connector type that matches the one you are using in your circuit. E.g 3.5 mm. Press Next button to change the connector type for Port 2. Once completed, press Back.
   Start calibration → Cal Wizard
   This will take you through 7 steps where you have to connect Port 1 and 2 to short, open, load, and through circuits in your calibration board. Once all 7 steps are completed, press Finish.
7. Your VNA is now calibrated.

Port extension

Port extension allows you to electrically move your measurement reference plane. For example, after calibration, you may add an extra transmission line. In such an instance, port extension is used to inform the analyser of this change. In this workshop, we use port extension as the VNA used in our experiment does not take into account the transmission lines added by the connectors on our boards.

- Connect the Open circuit in your SOLT board to the two ports of the VNA.
- Press Trace → Trace 1 → Measure → S_{11} → Format → Smith chart
  This step sets the parameter you want to display in Trace 1 in the form of a Smith chart. Repeat this step for Trace 2, 3, and 4 to display S_{12}, S_{21}, and S_{22}.
- Meas setup → Port extensions

去除伪‘传输线’影响

- Velocity factor - 0.85 (how much RF slows down in the PCB medium compared to free space)
- Port extensions - ON
- Port 1 extension - Adjust the delay until you see the open circuit on Smith chart
- Port 2 extension - Adjust the delay until you see the open circuit on Smith chart

Verifying calibration

- Connect the Short circuit of your SOLT calibration board to the VNA. Make sure you have Smith charts displayed in each trace.

  (Press Trace → Trace 1 → Measure → S_{11} → Format → Smith chart
  This step sets the parameter you want to display in Trace 1 in the form of a Smith chart. Repeat this step for Trace 2, 3, and 4 to display S_{12}, S_{21}, and S_{22}.)

Task 3:

- Discuss the Smith charts displayed in each trace. Does it show a Short circuit? Explain any deviations. **Important: You have to include the graphs of Smith charts for each S-parameter in the report**
- Repeat for Open, Load, and Through circuits in the SOLT calibration board.

Measuring S-parameters of unknown shunt and through impedances

You are required to measure the S-parameters of your circuit at 500 MHz frequency.

Shunt load

1. Connect the unknown shunt circuit to the VNA
2. Press Trace → Trace 1 → Measure → S_{11} → Format → Log mag
   Repeat this step for Trace 2, 3, and 4 to display S_{12}, S_{21}, and S_{22} in log magnitude.
3. Save/Recall → Device → USB
   Allows you to save your data to an USB
4. File type → Data(S2P) → Save
   You can find more information on how to use S2P data in the following links.
   http://na.support.keysight.com/plts/help/WebHelp/FilePrint/SnP_File_Format.htm
   https://ibis.org/connector/touchstone_spec11.pdf

Task 4:

- Using the S-parameter measurements taken and equation (4), calculate the two unknown shunt loads.

Through load

1. Connect the unknown through circuit to the VNA
2. Press Trace → Trace 1 → Measure → S_{11} → Format → Log mag
   Repeat this step for Trace 2, 3, and 4 to display S_{12}, S_{21}, and S_{22} in log magnitude.
3. Save/Recall → Device → USB
   Allows you to save your data to an USB
4. File type → Data(S2P) → Save

Task 5:

- Using the S-parameter measurements taken and equation (5), calculate the unknown through load.