

On-Board Calibration and Impedance Measurement

It is rather a simple task to measure the impedance of standard front connector (like type-F, BNC). Just connect the front connector to a network analyzer, then read out the impedance directly. It could be very tricky to measure the impedance at an internal point. Measuring the on-board impedance at an internal point, for instance the input port of an RF amplifier, is quite useful for debugging RF circuits. Below one traditional way is described and the shortages are pointed out. Then the easier and more accurate method using IMNLab is described.

Traditional On-Board Impedance Measurement

One way to measure the impedance at an internal point is to utilize a short extension cable, as shown in [Figure 1](#). One end of the cable is connected to the network analyzer cable. The other end is cut out and soldered to the PCB directly. The outer shield is soldered to the PCB ground and the center pin is soldered to the measurement point.

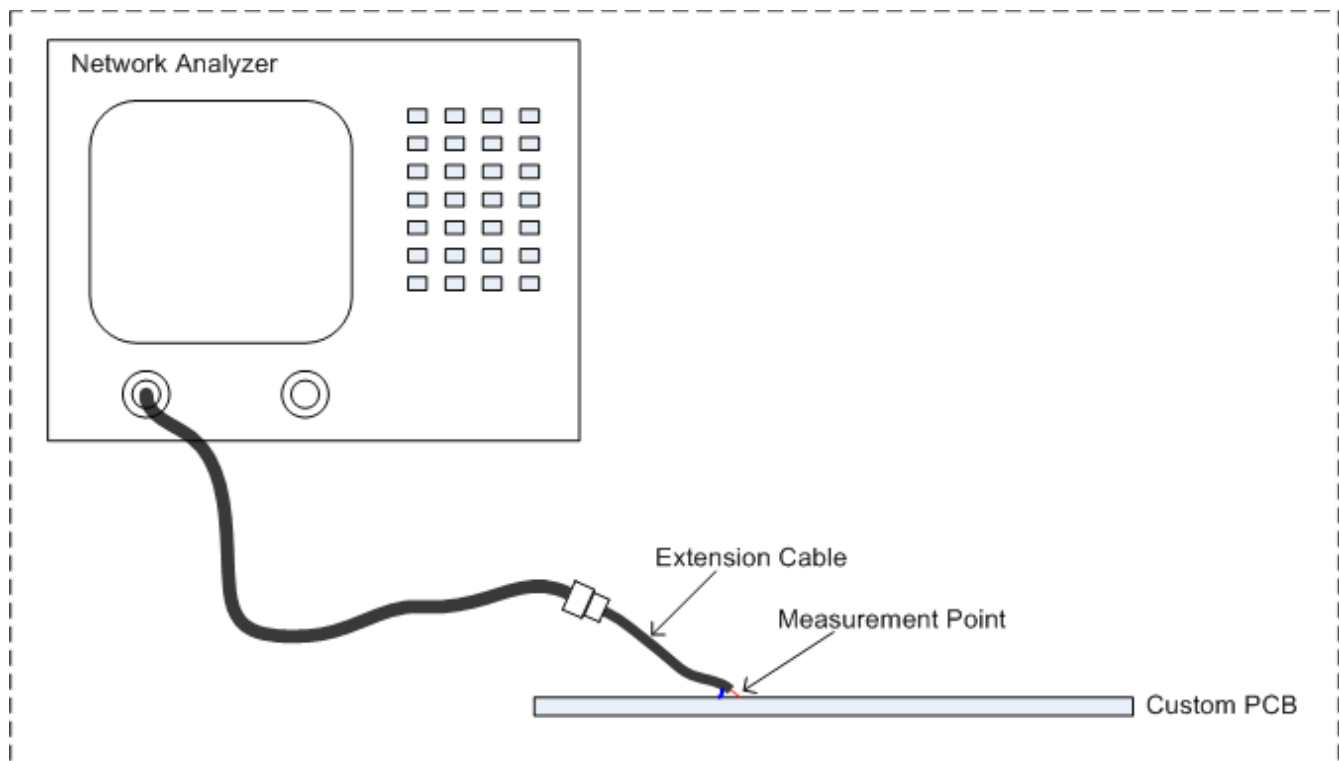


Figure 1. On-PCB impedance measurement method

The method shown in [Figure 1](#) can give accurate enough results if the frequency is low. To obtain accurate measurement at high frequency, the effect of extension cable must be calibrated away. Since there is no standard calibration kit for the cut-out end of the extension cable, custom calibration kit must be built to calibrate the network analyzer at the measurement point.

On-Board Impedance Measurement using IMNLab

With the help of appropriate PCB layout design, IMNLab reduces the manual work and obtains more accurate measurement for internal points. If there is no front connector connected to the measurement point, an extension cable is still needed. If the measurement point is connected to a front connector without excessive loss on the path, the front connector may be utilized to remove the soldering work of extension cable. Below both cases are discussed in details.

- **On-board impedance measurement without front-connector.**

When there is no front connector on PCB board or the front connector is not connected to the interested point, an extension cable is needed. This is similar to the method illustrated in [Figure 1](#) while no special instrument calibration is required. IMNLab will handle the calibration work of removing the non-ideal factors (delay, loss, etc.) of the extension cable. Another important advantage of using IMNLab is that the soldering point could be off the measurement point. The path from soldering point to the measurement point will be added to the extension cable. This feature may help quite a lot if the space around the measurement point is limited. As shown soon, this feature also eases the differential impedance measurement.

Four steps are needed to finish the measurement procedure utilizing IMNLab. The first three steps, named "**OPEN**", "**SHORT**" and "**MATCH**", are used for the calibration. The first three steps are similar to the calibration work for network analyzer with custom built calibration kit. The last step, named "**LOAD**", is to measure the impedance. This step is similar to connect a calibrated network analyzer to a front-connector to measure the impedance. The difference is that the result obtained is refer to the instrument calibration point. A map from instrument calibration point to the measurement point is needed to obtain the final result.

The examples for both single-ended and differential cases are shown in [Figure 2](#). The thin solid line represents idea electrical connection (no loss, no delay). It is the approximation of short tracks (with respect to wave length). Try the best to reduce the parasite effects. Such as solder one end of R directly on the measurement point and another end to the ground via or plane. The thick solid line represents long impedance controlled track without excessive loss. To reduce the loss on the path, the left side of the soldering point may be isolated by either cutting off the track or removing a serial component. The basic principle to find a "good" soldering point is to minimize the loss from measurement point to network analyzer. This will help increase measurement accuracy. An extreme "bad" example is that the soldering point is short-circuited to ground. In this case it is even not possible to measure anything.

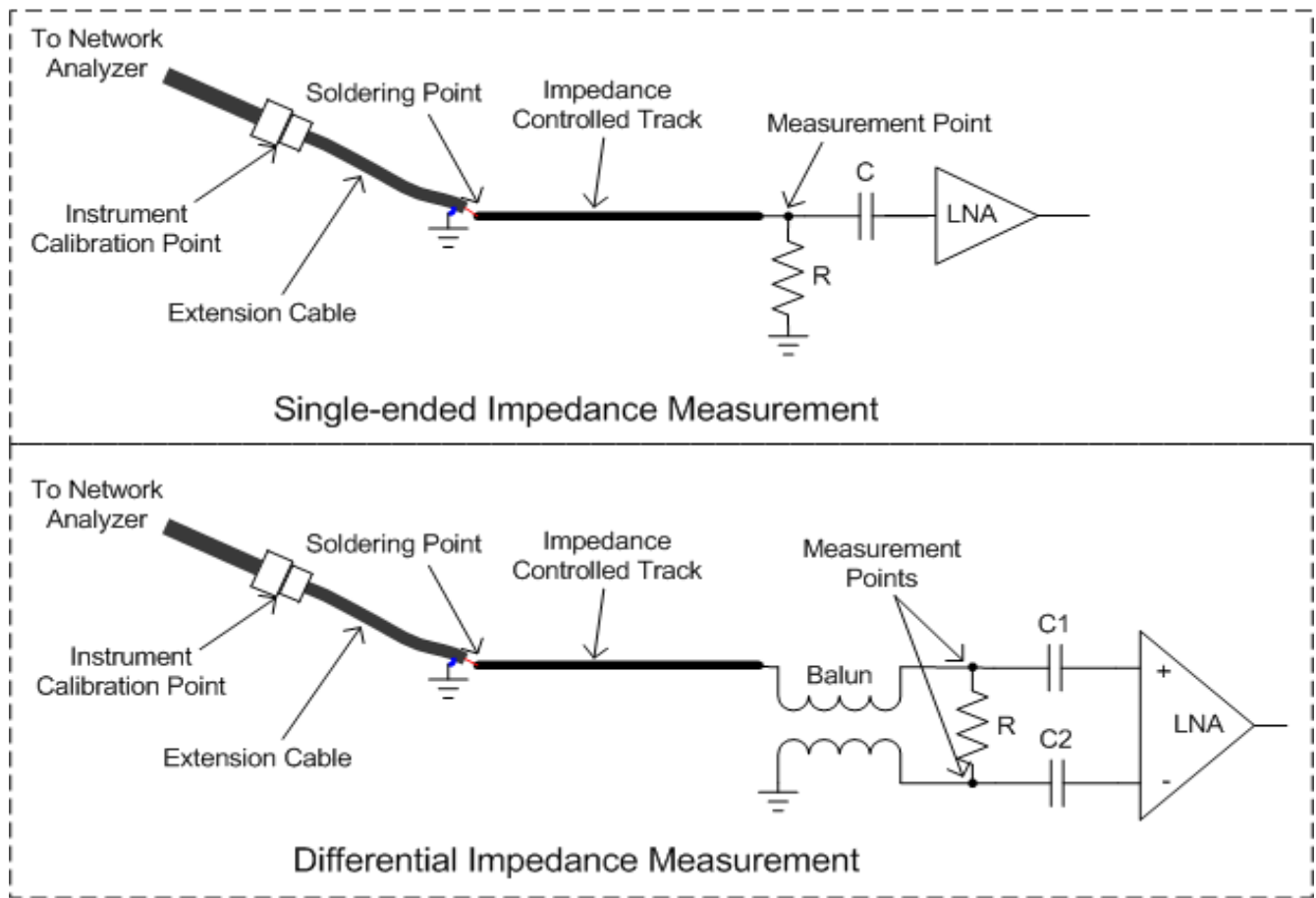


Figure 2. Examples for single-ended and differential impedance measurement

Before measuring something the network analyzer shall be calibrated refer to the instrument cable connector (refer to [Figure 2](#)). Choose the right calibration kit matching with the cable connector. For example, if the cable connector is 75Ω type-F connector, the instrument system impedance should be then set to 75Ω and a 75Ω type-F calibration kit should be used. Don't mess up the instrument system impedance and the board system impedance. It is pretty fine to use a 75Ω network analyzer to measure an RF circuit with 50Ω system impedance. Just regard the network analyzer as an advanced ohm meter. It is recommended to let network analyzer average over many readings to reduce the random errors during the calibration procedure.

After the instrument has been calibrated, pursue the below four steps to obtain the necessary information for the single-ended case:

1. **OPEN.** Remove shunt resistor R and serial capacitor C . Then average over 100 readings and save the data to disk in real-imag text format (Click [here](#) for more information about the file format). Any legal Windows file name *.dat could be used. But it is recommended to choose one easy to recognize. Simple "open.s1p" is a good choice. It is highly recommended to let network analyzer average over many readings to reduce the random errors and get smoother curve;
2. **SHORT.** Remove serial capacitor C and mount a zero ohm resistor as R . The tolerance of the resistor should be 1% or better. If AC-coupling is desired, mount R with a capacitor with low impedance in the whole band. Then average over 100 readings and save the data to disk. The recommended file name is "short.s1p";

3. **MATCH.** Remove serial capacitor C and mount R with a resistance equal to board system impedance. The tolerance of the resistor should be 1% or better. Note that the board system impedance refer to not the network analyzer, but the custom system. For example, if the system impedance of the network analyzer is 75Ω while the custom board is 50Ω , set R to 50Ω . Then average over 100 readings and save the data to disk. The recommended file name is "match.s1p";
4. **LOAD.** Remove shunt resistor R and mount serial coupling capacitor C. Choose a capacitor with low impedance in the whole band. Then average over 100 readings and save the data to disk. The recommended file name is "load.s1p".

The procedure for differential impedance measurement is similar to the that for single-ended case. A balun transformer is needed to convert the differential signal to single-ended. The extension cable shall not be soldered directly to the differential pairs (central pin to one line and shield to another line). Otherwise the coupling between the cable shield and the board ground plane will disturb the measurement results greatly. If the balun is not on the PCB board, it shall be installed manually. The non-idea factors (loss, delay, imbalance, etc.) of balun will be added to the path from measurement point to instrument calibration point and calibrated away by the software later. The whole measurement procedure for the differential case is described as:

1. **OPEN.** Remove shunt resistor R and serial capacitors C1 and C2. Then average over 100 readings and save the data to disk in *.s1p format. The recommended file name is "open.s1p";
2. **SHORT.** Remove serial capacitors C1 and C2, and mount a zero ohm resistor as R. The tolerance of the resistor should be 1% or better. If AC-coupling is desired, mount R with a capacitor with very low impedance in the whole band. Then average over 100 readings and save the data to disk. The recommended file name is "short.s1p";
3. **MATCH.** Remove serial capacitors C1 and C2, and mount R with the board system impedance as resistance. The tolerance of the resistor should be 1% or better. Then average over 100 readings and save the data to disk. The recommended file name is "match.s1p";
4. **LOAD.** Remove shunt resistor R and mount serial coupling capacitors C1 and C2. Choose the capacitors with very low impedance in the whole band. Then average over 100 readings and save the data to disk. The recommended file name is "load.s1p".

IMNLab utilizes the data obtained from "**OPEN**", "**SHORT**" and "**MATCH**" to build up the map from instrument calibration point to measurement point. Then it calculates the impedance at the measurement point by mapping the data obtained from "**LOAD**".

- **Impedance measurement of internal point with front connector.**

If the measurement point is connected to a front connector, the on-board impedance measurement is easier than that without front connector. The extension cable is not needed any more. Just connect the front connector to the network analyzer, then go through the four steps: "**OPEN**", "**SHORT**", "**MATCH**" and "**LOAD**".

In the examples shown in [Figure 3](#), an impedance match network is inserted to simultaneously demonstrate the two functionalities of IMNLab: impedance measurement and network optimization. Solid thin line represents ideal electrical connection while solid thick line represents impedance controlled track. The upper part of [Figure 3](#) shows a single-ended impedance match network. It is a Π network composed by three branches: two shunt branches R1-L1-C1 and R3-L3-C3, one serial branch R2-L2-C2. The lower part shows the differential variant: the serial branch is splitted into two branches in order to keep the symmetry of the

differential system. The differential variant should be avoided since it uses more components unless there is a special reason. There could be some components (for example directional-coupler) inserted between the measurement point and front connector as long as the loss on the path is not excessively high. When designing layout, place the components constituting impedance match network as close to each other as possible. This is to reduce the distributed effects. The inductors shall be vertical to each other for minimum magnetic coupling. For instance L1 and L3 should be placed vertical to L2. Since L1 and L3 are further apart, they can be placed in parallel.

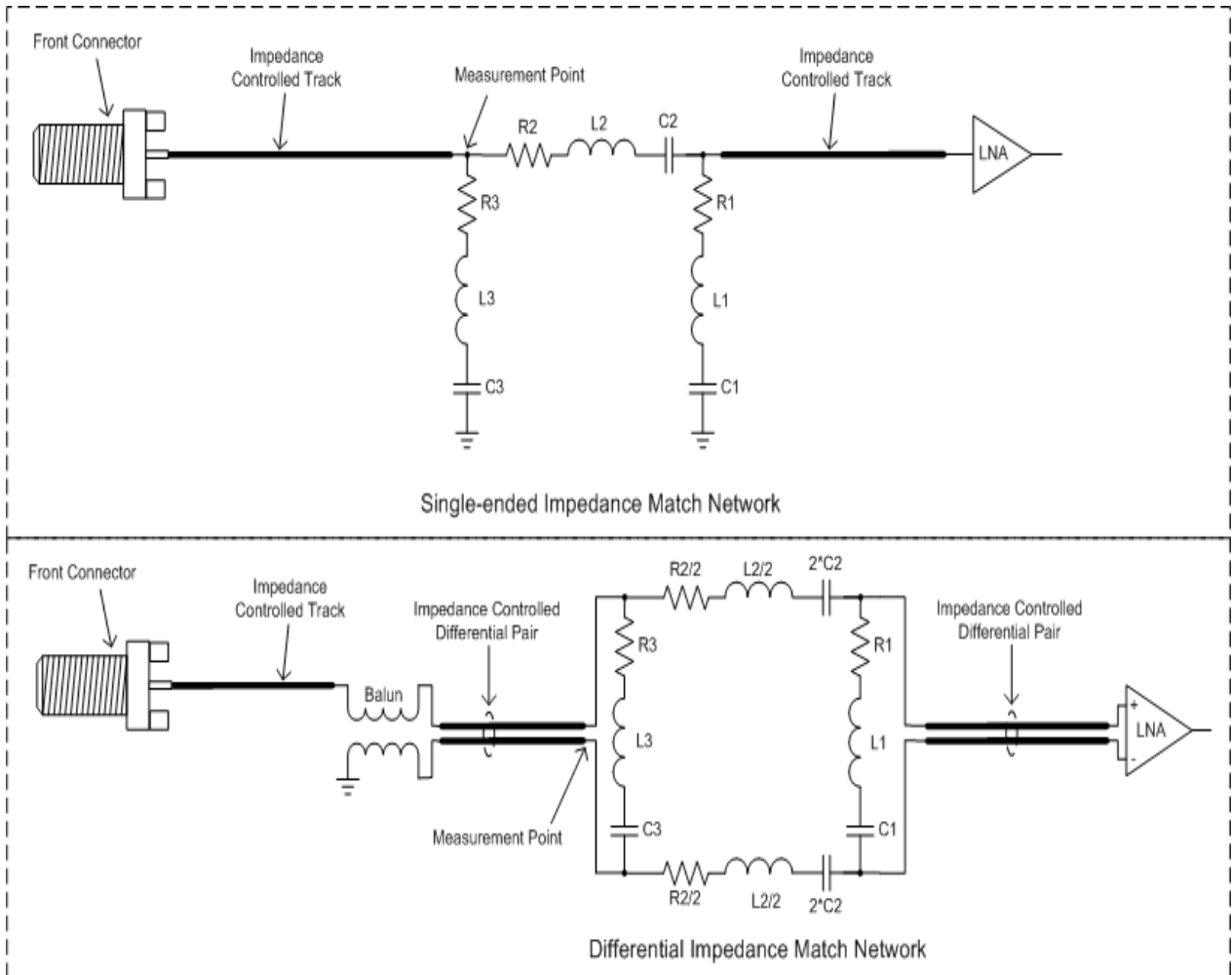


Figure 3. Examples of impedance match network for both single-ended and differential cases.

Make sure the network analyzer has been calibrated with the right calibration kit. It is recommended to let network analyzer average over many readings to reduce the random errors during the calibration procedure. Choose the right cable to match with the board front connector. An adapter may be used between the cable and the instrument if necessary. It is recommended that the instrument and the custom board have the same system impedance. However, the network analyzer system impedance could differ from the board impedance in some cases. For instance the network analyzer has 75Ω type-N front connector while the board front connector is 50Ω BNC. One solution is to use one 75Ω coaxial cable with 75 Ω type-F connectors at both ends, one 75Ω N-F adapter and one 75Ω type-F to 75Ω BNC adapter. The 75Ω N-F adapter is to connect the cable to the instrument. The 75Ω type-F to 75Ω BNC adapter is to connect the cable to the board front connector. Then calibrate the instrument with a 75Ω BNC calibration kit. Since

75Ω BNC connector is mechanically compatible to 50Ω BNC connector, it is possible to measure the impedance of the board connector.

After the instrument has been calibrated, pursue the below four steps for the single-ended case:

1. **OPEN.** Remove shunt branch R3-L3-C3 and serial branch R2-L2-C2. Then average over 100 readings and save the data to disk in real-imag text format (Click [here](#) for more information about the file format). The recommended file name is "open.s1p";
2. **SHORT.** Remove serial branch R2-L2-C2. And short shunt branch R3-L3-C3 by mounting all components with zero ohm resistor. If AC-coupling is desired, mount C3 with a capacitor with very low impedance in the whole band. The tolerance of the resistor should be 1% or better. Then average over 100 readings and save the data to disk. The recommended file name is "short.s1p";
3. **MATCH.** Remove serial branch R2-L2-C2. Mount L3 and C3 with zero ohm resistor. If AC-coupling is desired, mount C3 with a capacitor with low impedance in the whole band. Mount R3 with the resistance equal to board system impedance. The tolerance of the resistor should be 1% or better. Then average over 100 readings and save the data to disk. The recommended file name is "match.s1p";
4. **LOAD.** Remove shunt branches R1-L1-C1 and R3-L3-C3. Short serial branch R2-L2-C2 by mounting all components with zero Ω resistors. If AC-coupling is desired, mount C2 with a capacitor with very low impedance in the whole band. Then average over 100 readings and save the data to disk. The recommended file name is "load.s1p".

The procedure for the differential case (See [Figure 3](#), lower part) is very similar:

1. **OPEN.** Remove shunt branch R3-L3-C3 and two serial branches R2/2-L2/2-2*C2. Then average over 100 readings and save the data to disk in real-imag text format (Click [here](#) for more information about the file format). The recommended file name is "open.s1p";
2. **SHORT.** Remove the two serial branches R2/2-L2/2-2*C2. And short shunt branch R3-L3-C3 by mounting all components with zero ohm resistor. If AC-coupling is desired, mount C3 with a capacitor with very low impedance in the whole band. The tolerance of the resistor should be 1% or better. Then average over 100 readings and save the data to disk. The recommended file name is "short.s1p";
3. **MATCH.** Remove the two serial branches R2/2-L2/2-2*C2. Mount L3 and C3 with zero ohm resistor. If AC-coupling is desired, mount C3 with a capacitor with very low impedance in the whole band. Mount R3 with the resistance equal to board system impedance. The tolerance of the resistor should be 1% or better. Then average over 100 readings and save the data to disk. The recommended file name is "match.s1p";
4. **LOAD.** Remove shunt branches R1-L1-C1 and R3-L3-C3. Short the two serial branches R2/2-L2/2-2*C2 by mounting all components with zero ohm resistors. If AC-coupling is desired, mount C2 with a capacitor with very low impedance in the whole band. Then average over 100 readings and save the data to disk. The recommended file name is "load.s1p".

Now all information needed has been gathered. Import the four data files into IMNLab. The software will first calibrate the path from measurement point to front connector. Then the calibration data and the measured impedance are used by the optimization engine to search for optimal component values for either better return loss or higher power throughput.