ECE 4880: RF Systems

Fall 2016

Lab 2: Two-Port Signal Chain Component Characterization

1   Learning Objectives

The students will learn to:

1) Use the network analyzer (NA) to measure two-port RF modules
2) Understand the RF measurements from one-port and two-port network setup
3) Perform de-embedding procedures to extract the characteristics of RF modules
4) Extract circuit network from the de-embedding results
5) Understand the passive filter characteristics and SIMULINK description

2   Background Information

2.1   Network analyzer and S parameters

The network analyzer (NA) is an instrument that measures complex voltage transmission and reflection coefficients as a function of frequency for 2-port "networks". The 2-port network is frequently referred as "device under test" (DUT), as shown in Fig. 2.1. NA feeds in a test **monotone** sinusoidal voltage through TL1 and TL2 (labeled as v_{in1} and v_{in2}) to DUT, and simultaneously listens to the response on TL1 and TL2 (labeled as v_{out1} and v_{out2}). TL1 and TL2, and their corresponding subscripts in v_{in1}, v_{in2}, v_{out1} and v_{out2}, are from the NA point of view, where we can write a "**scattering matrix**" in Eq. (2.1) naturally. Notice that the signals here are labeled by the connecting cables of TL1 and TL2. The name "scattering" is derived from the physicists' view that a traveling wave/particle on TL1 is scattered in the DUT before continues on TL2.
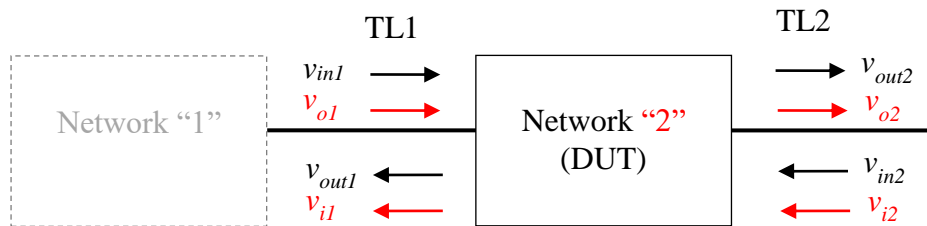
- Black: Labeled by TL1 and TL2
- Red: Labeled by Network 1 and 2

Fig. 2.1. Definition of traveling-wave voltages connected by a functional block.

$$\begin{bmatrix} v_{out1} \\ v_{out2} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}\begin{bmatrix} v_{in1} \\ v_{in2} \end{bmatrix} \qquad (2.1)$$

The scattering matrix derives its name from thinking free particles traveling on TL1 and TL2, and are then "scattered" through DUT, similar to a scattering center in the ideal gas or solid crystals. The DUT is often a module to be used in a RF signal chain. If we labeled the signal by the modules or networks, instead of the cables, v_{in1} becomes v_{o1} because it is the output of Network 1 (shown in grey in Fig. 3.1), v_{out1} becomes v_{i1} because it is the input to Network 1, v_{out2} becomes v_{o2} because it is the output of Network 2, and v_{in2} becomes v_{i2} because it is the input to Network 2. Now we can re-write Eq. (2.1) by the new Network notation:

$$\begin{bmatrix} v_{i1} \\ v_{o2} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} v_{o1} \\ v_{i2} \end{bmatrix} \tag{2.2}$$

We can now define the S-matrix element as a function of frequency as:

$$S_{11} \equiv \left. \frac{v_{out1}}{v_{in1}} \right|_{v_{in2}=0} \equiv \left. \frac{v_{i1}}{v_{o1}} \right|_{v_{i2}=0} \tag{2.3}$$

$$S_{21} \equiv \left. \frac{v_{out2}}{v_{in1}} \right|_{v_{in2}=0} \equiv \left. \frac{v_{o2}}{v_{o1}} \right|_{v_{i2}=0} \tag{2.4}$$

$$S_{12} \equiv \left. \frac{v_{out1}}{v_{in2}} \right|_{v_{in1}=0} \equiv \left. \frac{v_{i1}}{v_{i2}} \right|_{v_{o1}=0} \tag{2.5}$$

$$S_{22} \equiv \left. \frac{v_{out2}}{v_{in2}} \right|_{v_{in1}=0} \equiv \left. \frac{v_{o2}}{v_{i2}} \right|_{v_{o1}=0} \tag{2.6}$$

NA uses standard 50 Ω connection at its two ports, which connect to DUT by TL1 and TL2. Most microwave coaxial cables[1] are designed to either 50Ω or 75Ω with respective bandwidths of operation. Microwave cables are waveguides and are characterized by their **characteristic impedance** (Ω), **operation bandwidth** (Hz), **cable insertion loss** (dB/m as a function of frequency) and **isolation** (dB as function of frequency). For example, one of the most popular convenient microwave cables for PCB is the SMA (sub miniature version A) cable, which uses a 4.2 mm diameter outer coax, filled with PTFE dielectric[2]. The upper frequency limit is anywhere from 18 to 26 GHz, depending on the tolerances held during manufacturing. SMAs are sized to fit a 5/16 inch wrench, and mate with 3.5mm and 2.92mm connectors. Two other popular cables within the communication frequency range of 100MHz to 40GHz include BNC (Bayonet type-N connector or baby N connector), which is popular in cable video connection) and N-type (named after the developer Paul Neill of Bell Labs, available in both 50Ω and 75Ω), which is popular in microwave instrument. As cables connect parts to parts, there are always male and female connection choices. Examples of cables, connectors and converters are shown in Fig. 2.2.

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[1] Due to the long history of RF, microwave and radar development, there are a myriad of selections of cables, connectors, and converters. A full long table of these choices and their acronyms can be found in: http://www.microwaves101.com/encyclopedias/microwave-connectors

[2] PTFE: Poly-tetrafluoro-ethylene, also called Teflon, is the low loss RF media and resistant to most known chemicals.

The connectors out of the Keysight NA in our lab are labeled "Port 1" and "Port 2" with N-type female. Measurements from NA naturally match to the S parameters in Eq. (2.1). For example, when Port 1 sends a test sinusoidal voltage, the response measured at Port 2 is S_{21}, and the response at Port 1 is S_{11}. Similarly, when Port 2 sends a test sinusoidal voltage, the response measured at Port 1 is S_{12}, and the response at Port 2 is S_{22}.

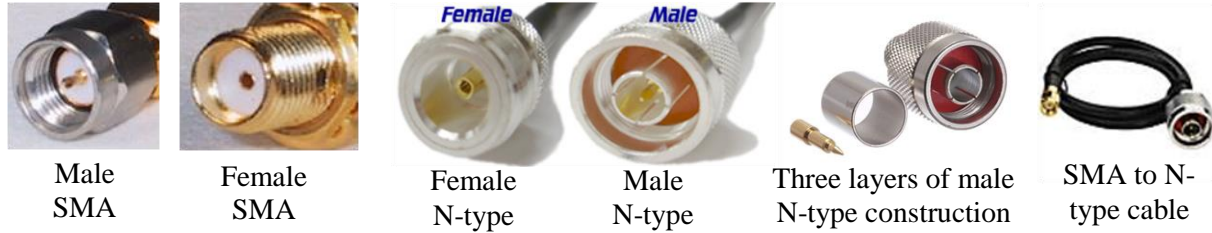| Male SMA | Female SMA | Female N-type | Male N-type | Three layers of male N-type construction | SMA to N-type cable |

Fig. 2.2. Examples of microwave connectors, cables and converters.

Although the S parameters are convenient and clear in the component measurement, they cannot be cascaded by matrix multiplication, as the vectors in Eq. (2.2) contain components originated from different networks. By using Eqns. (2.3) – (2.6), we can define the **T matrix**:

$$\begin{bmatrix} v_{o1} \\ v_{i1} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} v_{o2} \\ v_{i2} \end{bmatrix} \quad (2.7)$$

From definition, the S and T matrices are related by:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{S_{21}} \begin{bmatrix} 1 & -S_{22} \\ S_{11} & S_{12}S_{21} - S_{11}S_{22} \end{bmatrix} \quad (2.8)$$
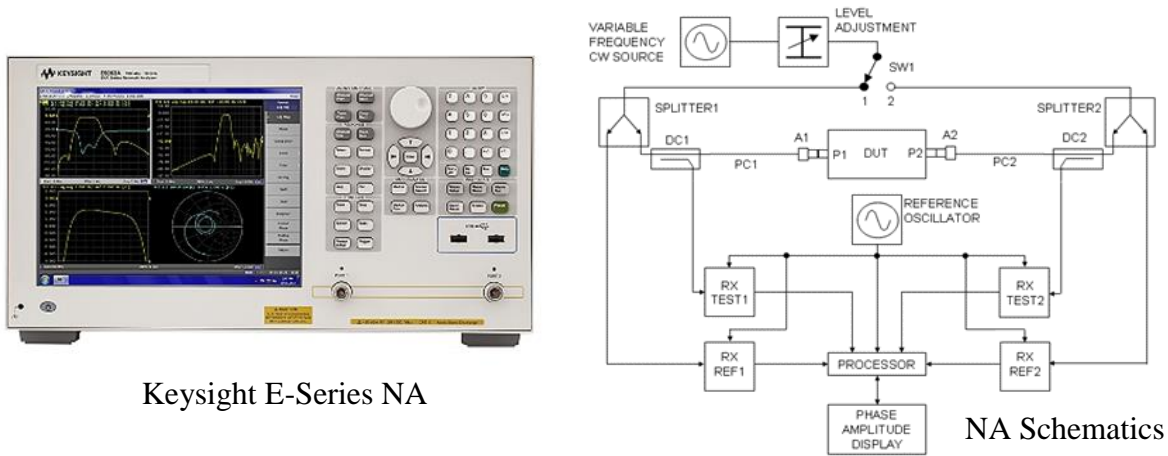
$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{T_{11}} \begin{bmatrix} T_{21} & T_{11}T_{22} - T_{12}T_{21} \\ 1 & -T_{12} \end{bmatrix} \quad (2.9)$$

2.2 De-embedding for device under test

As cables and connectors are also microwave components, they can be part of the network with non-ideal responses as a function of frequency. Notice that this is very different from the point of view of a jump wire in quasi-static circuits, which can be treated as a simple circuit node. Although the cables and connectors are often made into rather precise 50Ω characteristic impedance or I/O impedance, not only there can be non-ideal distortion in different frequencies, but also their impedance and length will play a role when the input and output impedances of the DUT are not well matched to 50Ω (remember your Smith Chart?). The connection from NA to DUT can be viewed as three S matrices in cascade between Port 1 and Port 2, as shown in Fig. 2.3. To obtain the true S matrix of DUT, we will perform the de-embedding procedure. Notice that NA is similar to the transceiver architecture in Fig. 2.3, where RX1 and RX2 listens to the LO excitation at Port 1 and Port 2. NA is sometime called the "vector" network analyzer, as there can be more than 2 ports (4 ports are another popular option).

Historically there are two most popular de-embedded methods: SOLT (short-open-load-through) and TL (through only). SOLT uses known one port response (SOL) to characterize each port, and then T to determine the coupling between Port 1 and Port 2. As the procedure for characterizing the assumed

network is very complicated, most NAs provide calibration kits and programs to do this automatically and hide the SOLT de-embedding procedure from the user. This is not only problematic for educational purposes, but the black-box procedure also makes estimation of errors much more difficult.
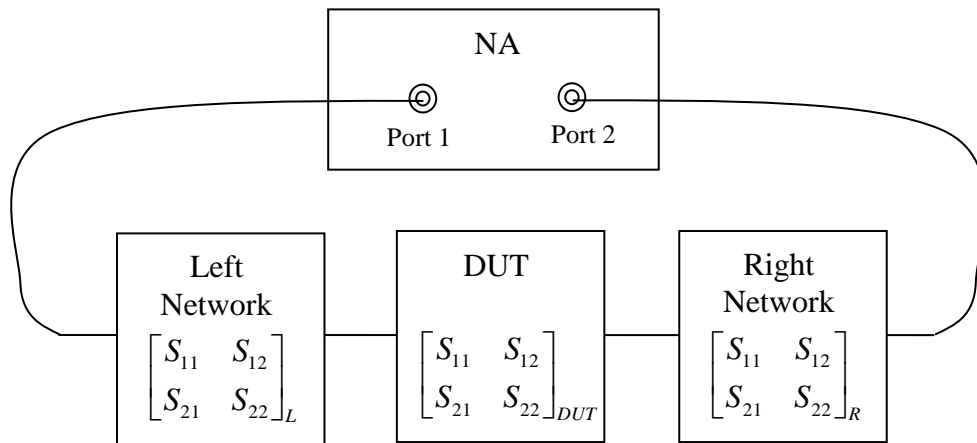

Keysight E-Series NA

NA Schematics

Left Network

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_L$$

DUT

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_{DUT}$$

Right Network

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_R$$

Fig. 2.3. Network analyzer connection to DUT. In order to measure the true DUT, we need to de-embed the influence for both left and right connections, described by their respective S matrices.

We will use the TL de-embedding method in all of our labs when NA is used, and we will make the steps as transparent as possible. In theory, there is no sacrifice in accuracy by using TL instead of SOLT, and the user can see the error estimate of the DUT clearly. The secret lies in the symmetry of the test setup. If we are careful in making the connection, we can make the right network to be a mirror image of the left network. By making two measurements, one with DUT (T_{meas}) and the other without (T_{thru}), as shown in Fig. 2.4, we can use the following steps to find S_{DUT}.

First we will assume the left and right networks can be well represented by mirrored L-sections with $Z/2$ cross and Y parallel component. Notice that both Z and Y are complex numbers and can represent simple RLC network in parallel or in series. We will first convert the measured S_{thru} to Y_{thru} from the following formula (all matrix elements are complex numbers). Notice the symmetry in the assumed through network for their S and Y matrix representations.

$$Y_{thru} = \begin{bmatrix} y_{11} & y_{12} \\ y_{12} & y_{11} \end{bmatrix} = \frac{1}{Z_0} \begin{bmatrix} \dfrac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}} & \dfrac{-2S_{12}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}} \\ \dfrac{-2S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}} & \dfrac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}} \end{bmatrix} \qquad (2.10)$$

If the connecting cables are well matched, then we should obtain symmetric S parameters in the first place, i.e., $S_{11} = S_{22}$ and $S_{12} = S_{21}$. Any mismatch will be an indication of the mismatch inside the Port 1 and Port 2, or the connecting cables. As TL de-embedding relies on the symmetry, serious mismatch in the S parameters will indicate that NA needs to be re-calibrated or better cables are needed. Notice that if SOLT is used, these kinds of internal error cannot be easily corrected either.
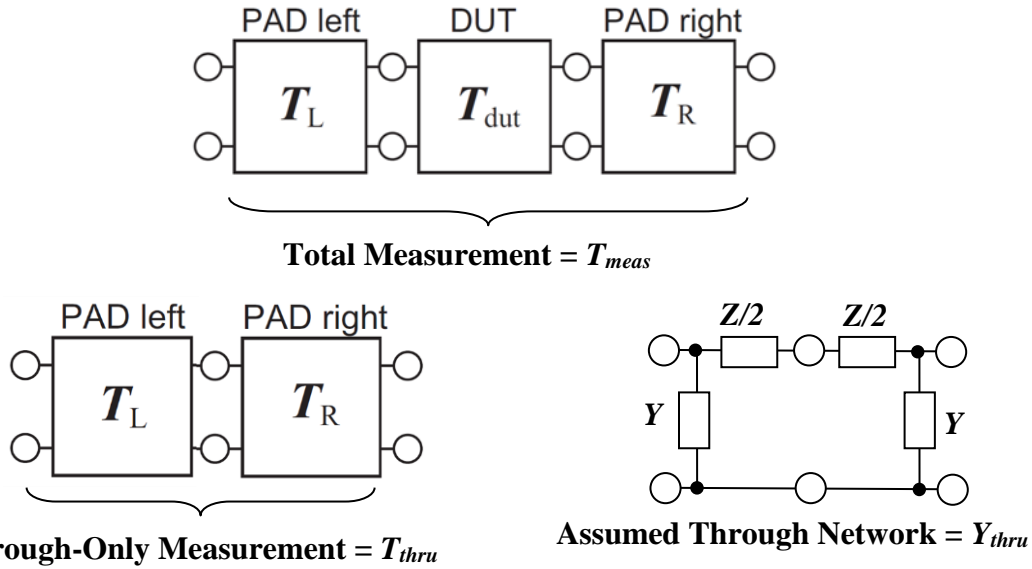

Fig. 2.4. Distributive view of "Through-Only" (TL) de-embedding. The T_L and T_R can be determined from the through-only measurements by considering symmetry in the physical connection.

After obtaining the two complex numbers of y_{11} and y_{12}, the left and right network can be expressed as:

$$Y_L = \begin{bmatrix} Y + \dfrac{2}{Z} & -\dfrac{2}{Z} \\ -\dfrac{2}{Z} & \dfrac{2}{Z} \end{bmatrix}; \quad Y_R = \begin{bmatrix} \dfrac{2}{Z} & -\dfrac{2}{Z} \\ -\dfrac{2}{Z} & Y + \dfrac{2}{Z} \end{bmatrix} \qquad (2.11)$$

where

$$Y = y_{11} + y_{12}; \quad Z = -\frac{1}{y_{12}} \qquad (2.12)$$

We can use Eqs. (2.11) and (2.12) to calculate T_L and T_R, which is rather complicated transformation, so you can do it from the intermediate S_L and S_R, or the following direct Y to T conversion, where the cable characteristic admittance $Y_0 = 1/Z_0$:

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$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} -\dfrac{(Y_0+Y_{11})(Y_0+Y_{22})-Y_{12}Y_{21}}{2Y_0Y_{21}} & \dfrac{(Y_0+Y_{11})(Y_0-Y_{22})+Y_{12}Y_{21}}{2Y_0Y_{21}} \\ -\dfrac{(Y_0-Y_{11})(Y_0+Y_{22})+Y_{12}Y_{21}}{2Y_0Y_{21}} & \dfrac{Y_0^4-Y_0^2(Y_{11}^2+Y_{22}^2+2Y_{12}Y_{21})+Y_{11}^2Y_{22}^2+Y_{12}^2Y_{21}^2-2Y_{11}Y_{12}Y_{21}Y_{22}}{2((Y_0+Y_{11})(Y_0+Y_{22})-Y_{12}Y_{21})Y_0Y_{21}} \end{bmatrix} \quad (2.13)$$

After obtaining the numerical values in T_L and T_R, because we know:

$$T_{meas} = T_L T_{DUT} T_R$$
$$T_{through} = T_L T_R \qquad (2.14)$$

We can therefore calculate T_{DUT} by:

$$T_{DUT} = T_L^{-1} T_{meas} T_R^{-1} \qquad (2.15)$$

We can then use Eq. (2.9) to obtain the de-embedded S_{DUT}, or the right-hand side of Eq. (2.10) to obtain the de-embedded Y_{DUT}.

3   Lab Procedures

3.1   Understanding the importance of termination in NA

1. Turn on the Keysight NA. To protect the NA N-type female connectors at Port 1 and Port 2, NEVER unscrew the N-type-to-SMA connectors on NA.
2. Connect a SMA cable to Port 1, and leave Port 2 with just the N-type-to-SMA connector. Measure the S parameters from 500MHz to 3GHz. Notice that both ports are looking at "Open" in a different sense. Observe the four S parameters as complex numbers. The following steps will be helpful on the Network Analyzer:
    (a) Set the frequency using 'Start' and 'Stop' keys. The units are selected from unit keys close to numeric keypad. Use 'Autoscale' to adjust the view.
    (b) Use 'Measure' key and select the S parameters. Under that menu, you can choose the format – (magnitude/phase) or (real/imaginary). Observe and save in polar format (magnitude/phase). The default unit for magnitude is in dB, and the default unit for phase is degree (between –180° and 180°).
    (c) You can save the trace by using 'Save' key → Save the trace. The data will be saved in a file with extension .csv. The first column shows the frequency and the second and third columns show corresponding S parameter values in the unit you set in step 2(b).

3.2   Measuring the filters by the 2-port network representation

1. Obtain two SAW (surface-acoustic-wave) filters, two matched SMA cables and one through-SMA connector from the TA. The filter has a center frequency of 1575.42 MHz and band pass width of 60 MHz.
2. Measure S_{thru} in the configuration of cable-through-cable with the two cables connected with a SMA male-male connector. Set the center frequency as 1.575 GHz and span as 200 MHz using 'Center' and 'Span' keys. Save all the S parameters as complex numbers.

3. Obtain S_{meas} of each SAW filter by replacing the filter at the through-connector position in the same frequency range. Save these S-parameters. Since the filter has a SMA male connector at one end and female at another, you will have to insert the male-male connector as well to make the connection.
4. Obtain S_{meas} of the two SAW filters in series, connected through the SMA male-male connector. Record the result to your computer.

4   Optional Explorations

1. What measurements can you do to further observe the symmetry in your test setups?
2. What measurements can you do to know whether the filter implementation is symmetric for its inside network (such as in T and Pi networks)?

5   Report Guidelines

In addition to the NA measurements, there are significant post processing of data you need to perform in Matlab or Excel. It would be useful that you write the program in advance, and test them with ideal bandpass filter behavior (0dB in pass band and -80dB in stop band). You may then complete the de-embedded process during the experiment period to make sure you have sufficient and qualitatively correct data.

The main purpose of the lab report is to present findings (and enable people to trace, and repeat if necessary) of your results. Therefore, the ambient information can be as important as the direct results from the instrument. The following content is suggested, but not meant as a template or limitation.

1. Brief description of the lab
2. Brief description of instruments
3. Brief description of the procedures
4. Measurement results in 3.1. How is the "open" response at Port 1 and Port 2? Is there any observable S_{12} or S_{21}, which may come from the internal leakage?
5. Obtain the T_L and T_R matrices in 3.2 at all recorded frequency points. Record any observable asymmetric behavior.
6. Plot Re(Y), Im(Y), Re(Z) and Im(Z) in Eq. (2.12) from the through matrix Y_{thru} as a function of frequency. Are they strong functions of frequency?
7. Perform the de-embedding procedure for each S_{meas} setup. Plot S_{DUT} in magnitude and phase for each SAW filter across the entire frequency range. You should put $S_{11DUT\_filter1}$, $S_{11DUT\_filter2}$, $S_{22DUT\_filter1}$ and $S_{22DUT\_filter2}$ in the same magnitude and phase plots for clear comparison. Do the same for $S_{12DUT\_filter1}$, $S_{12DUT\_filter2}$, $S_{21DUT\_filter1}$ and $S_{21DUT\_filter2}$ in magnitude and phase plots.
8. Repeat Step 7 but comparing Filter 1 and the series of Filter 1 and Filter 2.
9. Describe Filter 1 and the series of Filter 1 and Filter 2 in the Matlab Simulink module. Create a test voltage source with the following property: (1) signal source frequency: 500MHz, 915MHz, 1.8MHz and 2.4GHz; (2) Amplitude of output signal: 0.1V; (3) Phase noise level -60dBc/Hz @ 100Hz offset (this will be clear later). Record the output of the filter driven by the signal source.

For report submission, please name your lab reports as: netid_netid_ECE4880_Lab1 for two students in a lab group. Submit your final report in Word or pdf to kan@ece.cornell.edu. The report should be by each group. Submit your Matlab script or Excel sheet for the de-embedding procedure as a separate file.

A conversion table for the network matrix representation from Pozar's book is attached at the end of the lab handout. Further reading and tables can be found on Blackboard.

	S	Z	Y	$ABCD$
S_{11}	S_{11}	$\dfrac{(Z_{11}-Z_0)(Z_{22}+Z_0)-Z_{12}Z_{21}}{\Delta Z}$	$\dfrac{(Y_0-Y_{11})(Y_0+Y_{22})+Y_{12}Y_{21}}{\Delta Y}$	$\dfrac{A+B/Z_0-CZ_0-D}{A+B/Z_0+CZ_0+D}$
S_{12}	S_{12}	$\dfrac{2Z_{12}Z_0}{\Delta Z}$	$\dfrac{-2Y_{12}Y_0}{\Delta Y}$	$\dfrac{2(AD-BC)}{A+B/Z_0+CZ_0+D}$
S_{21}	S_{21}	$\dfrac{2Z_{21}Z_0}{\Delta Z}$	$\dfrac{-2Y_{21}Y_0}{\Delta Y}$	$\dfrac{2}{A+B/Z_0+CZ_0+D}$
S_{22}	S_{22}	$\dfrac{(Z_{11}+Z_0)(Z_{22}-Z_0)-Z_{12}Z_{21}}{\Delta Z}$	$\dfrac{(Y_0+Y_{11})(Y_0-Y_{22})+Y_{12}Y_{21}}{\Delta Y}$	$\dfrac{-A+B/Z_0-CZ_0+D}{A+B/Z_0+CZ_0+D}$
Z_{11}	$Z_0\dfrac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{11}	$\dfrac{Y_{22}}{|Y|}$	$\dfrac{A}{C}$
Z_{12}	$Z_0\dfrac{2S_{12}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{12}	$\dfrac{-Y_{12}}{|Y|}$	$\dfrac{AD-BC}{C}$
Z_{21}	$Z_0\dfrac{2S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{21}	$\dfrac{-Y_{21}}{|Y|}$	$\dfrac{1}{C}$
Z_{22}	$Z_0\dfrac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{22}	$\dfrac{Y_{11}}{|Y|}$	$\dfrac{D}{C}$
Y_{11}	$Y_0\dfrac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\dfrac{Z_{22}}{|Z|}$	Y_{11}	$\dfrac{D}{B}$
Y_{12}	$Y_0\dfrac{-2S_{12}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\dfrac{-Z_{12}}{|Z|}$	Y_{12}	$\dfrac{BC-AD}{B}$
Y_{21}	$Y_0\dfrac{-2S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\dfrac{-Z_{21}}{|Z|}$	Y_{21}	$\dfrac{-1}{B}$
Y_{22}	$Y_0\dfrac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\dfrac{Z_{11}}{|Z|}$	Y_{22}	$\dfrac{A}{B}$
A	$\dfrac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}$	$\dfrac{Z_{11}}{Z_{21}}$	$\dfrac{-Y_{22}}{Y_{21}}$	A
B	$Z_0\dfrac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}$	$\dfrac{|Z|}{Z_{21}}$	$\dfrac{-1}{Y_{21}}$	B
C	$\dfrac{1}{Z_0}\dfrac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}}$	$\dfrac{1}{Z_{21}}$	$\dfrac{-|Y|}{Y_{21}}$	C
D	$\dfrac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}}$	$\dfrac{Z_{22}}{Z_{21}}$	$\dfrac{-Y_{11}}{Y_{21}}$	D

$|Z|=Z_{11}Z_{22}-Z_{12}Z_{21}$; $\quad |Y|=Y_{11}Y_{22}-Y_{12}Y_{21}$; $\quad \Delta Y=(Y_{11}+Y_0)(Y_{22}+Y_0)-Y_{12}Y_{21}$; $\quad \Delta Z=(Z_{11}+Z_0)(Z_{22}+Z_0)-Z_{12}Z_{21}$; $\quad Y_0=1/Z_0$.