S-Parameter Simulation with ADS

1) Objective:

To setup and execute S-parameter simulation, to display simulation data, and to use SNP files in ADS

2) Theory:

The abbreviation (S) has been derived from the word scattering. The scattering matrix provides a complete description of the network as seen at its (N) ports. The scattering matrix relates the voltage waves incident on the ports to those reflected from the ports.

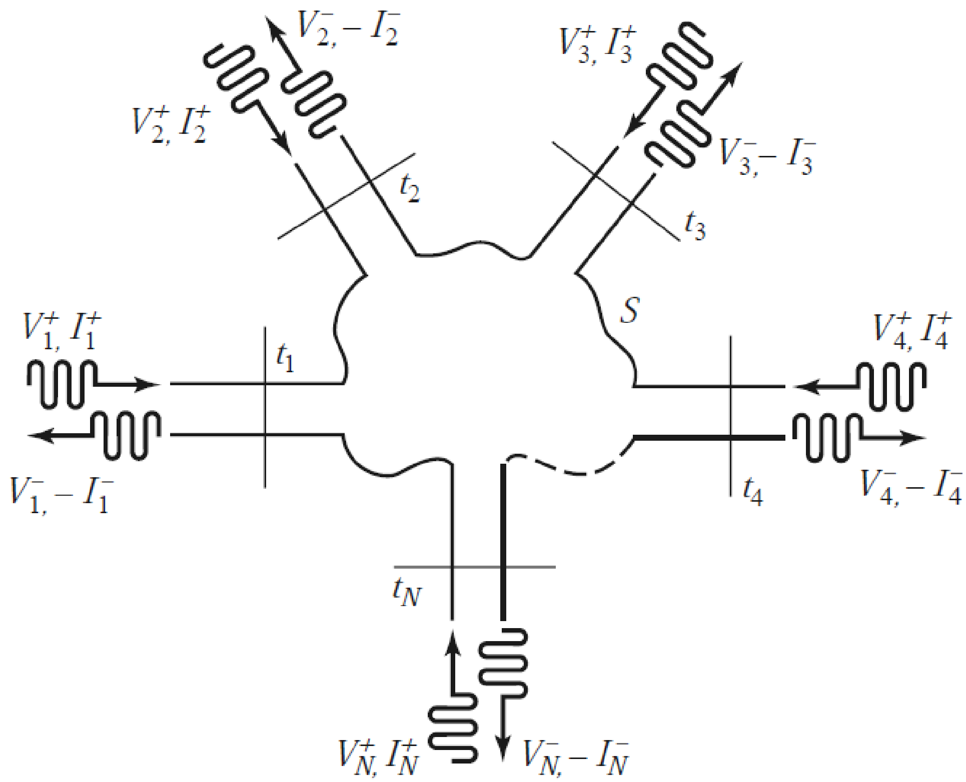

Figure 1: An *N*-port Microwave Network

Consider the N-port network shown in figure 1, where the voltages with positive superscripts denote the amplitude of the voltage wave incident on a port, and voltages with negative superscripts represent the amplitude of the voltage wave reflected from a port. The scattering matrix, or S-matrix, is defined in relation to these incident and reflected voltage waves as:

$$[V^-] = [S][V^+]$$

The above equation can be expanded to give the following expression:

$$\begin{bmatrix} V_1^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

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A specific element of the scattering matrix can be determined as:

$$S_{ij} = \left.\frac{V_i^-}{V_j^+}\right|_{V_k^+=0\ for\ k\neq j}$$

The value (S_{ij}) is found by driving port (j) with an incident wave of voltage (V_j^+) and measuring the reflected wave amplitude (V_i^-) coming out of port (i). The incident waves on all ports except the jth port are set to zero, which means that all ports should be terminated in matched loads to avoid reflections.

(S_{ii}) is the reflection coefficient seen looking into port (i) when all other ports are terminated in matched loads. (S_{ij}) is the transmission coefficient from port (j) to port (i) when all other ports are terminated in matched loads.

The total voltage and current on a transmission line in terms of the incident and reflected voltage wave amplitudes are given by:

$$V = V_0^+ + V_0^-$$

$$I = \frac{1}{Z_0}(V_0^+ + V_0^-)$$

In the above equation, Z_0 is the characteristic impedance of the line. The incident and reflected voltage wave amplitudes in terms of the total voltage and current are given by:

$$V_0^+ = \frac{V + Z_0 I}{2}$$

$$V_0^- = \frac{V - Z_0 I}{2}$$

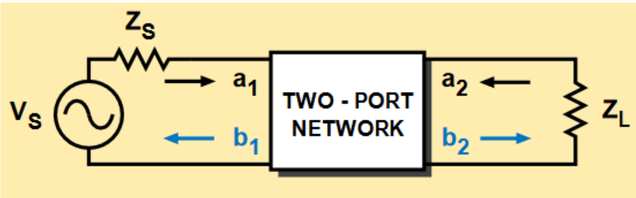

Figure 2: Incident and Reflected Waves

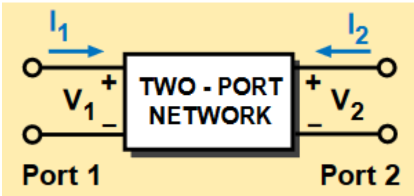

Figure 3: Terminal Voltages and Currents

The variables (a_i) and (b_i) are normalized complex voltage waves incident on and reflected from the ith port of the network. They are defined in terms of the terminal voltage (V_i), the terminal current (I_i) and an arbitrary reference impedance (Z_i):

$$a_i = \frac{V_i + Z_i I_i}{2\sqrt{|Re\ Z_i|}}$$

$$b_i = \frac{V_i - Z_i^* I_i}{2\sqrt{|Re\ Z_i|}}$$

For most measurements and calculations it is convenient to assume that the reference impedance (Z_i) is positive and real. All variables and parameters will be referenced to a positive real impedance (Z_0).

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The independent variables (a_1) and (a_2) are normalized incident voltages:

$$a_1 = \frac{V_1 + I_1 Z_0}{2\sqrt{Z_0}} = \frac{voltage\ wave\ incident\ on\ port\ 1}{\sqrt{Z_0}} = \frac{V_{i1}}{\sqrt{Z_0}}$$

$$a_2 = \frac{V_2 + I_2 Z_0}{2\sqrt{Z_0}} = \frac{voltage\ wave\ incident\ on\ port\ 2}{\sqrt{Z_0}} = \frac{V_{i2}}{\sqrt{Z_0}}$$

The dependent variables (b_1) and (b_2) are normalized reflected voltages:

$$b_1 = \frac{V_1 - I_1 Z_0}{2\sqrt{Z_0}} = \frac{voltage\ wave\ reflected\ from\ port\ 1}{\sqrt{Z_0}} = \frac{V_{r1}}{\sqrt{Z_0}}$$

$$b_2 = \frac{V_2 - I_2 Z_0}{2\sqrt{Z_0}} = \frac{voltage\ wave\ reflected\ from\ port\ 2}{\sqrt{Z_0}} = \frac{V_{r2}}{\sqrt{Z_0}}$$

The linear equations describing the two port network are:

$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

The s-parameters S_{11}, S_{22}, S_{21}, S_{12}, are:

$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$ Input reflection coefficient with the output port terminated by a matched load

$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$ Output reflection coefficient with the input port terminated by a matched load

$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$ Forward transmission gain with the output port terminated in a matched load

$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$ Reverse transmission gain with the input port terminated in a matched load

The following observation can be made:

$$S_{11} = \frac{b_1}{a_1} = \frac{\frac{V_1}{I_1} - Z_0}{\frac{V_1}{I_1} + Z_0} = \frac{Z_1 - Z_0}{Z_1 + Z_0}$$

$$Z_1 = Z_0 \frac{(1 + S_{11})}{(1 - S_{11})} = \frac{V_1}{I_1} = input\ impedance\ at\ port\ 1$$

Thus, the reflection coefficients S_{11} and S_{22} can be converted directly to impedance, and manipulated to determine matching networks for optimizing a circuit design.

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3) Lab Exercises:

1) The scattering matrix of a two-port network is given as:

$$S_{50\Omega} = \begin{bmatrix} 5/13 & j12/13 \\ j12/13 & 5/13 \end{bmatrix}$$

The port impedance is $Z_0 = 50\Omega$.

(a) Create a (*.snp) file as shown in figure 4, using the given scattering parameters
- ➢ SNP stands for the following: s = s-parameters, n = number of ports, p = port
- ➢ Example: For 2 port network, snp = s2p

(b) Format of a (*.snp) file is as follows:
- ➢ The line with the sharp symbol (#) defines the format of the subsequent lines
- ➢ GHz = Frequency to be given in GHz
- ➢ S = S-parameters to be given in the format of Magnitude and Angle (MA)
- ➢ R = Port reference impedance which in this case is set to 50Ω
- ➢ Lines with an exclamation mark (!) are comment lines

(c) In this problem the s-parameters do not vary with frequency
- ➢ To plot the s-parameters with ADS an arbitrary frequency range from 1GHz to 2 GHz is chosen
- ➢ The S-parameter data is given in decimal nomination

#	**GHz S**	**MA**	**R 50**					
! freq	**magS11**	**angS11**	**magS21**	**angS21**	**magS12**	**angS12**	**magS22**	**angS22**
! freq	**5/13**	**0 deg**	**12/13**	**90 deg**	**12/13**	**90 deg**	**5/13**	**0 deg**
1.0	**0.3846153846**	**0**	**0.923076923**	**90**	**0.923076923**	**90**	**0.3846153846**	**0**
2.0	**0.3846153846**	**0**	**0.923076923**	**90**	**0.923076923**	**90**	**0.3846153846**	**0**

Figure 4: Format of s2p File for S-Parameter Definition

(d) Create a schematic as shown in figure 5
- ➢ Place a SNP element (in this case S2P) in the schematic window using **Data Items palette** in ADS
- ➢ Import the (*.s2p) file into the SNP element
- ➢ Perform two port simulation using S2P element (Start = 1 GHz, Stop = 2 GHz, Step = 100 MHz)

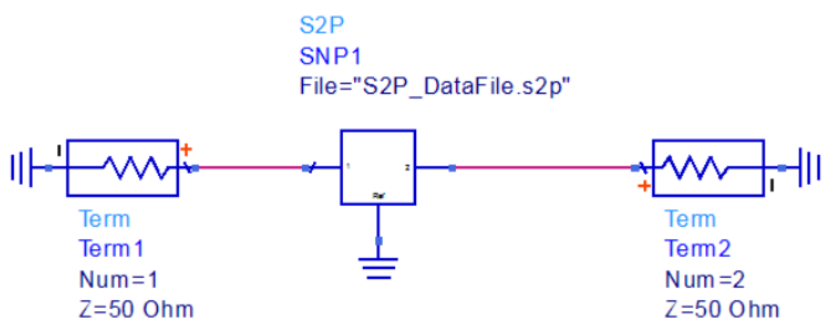

Figure 5: Schematic of Simulating S-Parameters using SNP File

(e) Use **rectangular plot** to show **magnitude** and **phase** of the scattering parameters versus frequency
(f) Use a **list plot** to **tabulate** the four scattering parameters (S_{11}, S_{12}, S_{21}, S_{22}) versus frequency

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2) Repeat the process of the 1st problem using the following scattering matrix:

$$S_{50\Omega} = \begin{bmatrix} 0.3 + j0.7 & j0.6 \\ j0.6 & 0.3 - j0.7 \end{bmatrix}$$

The port impedance is $Z_0 = 50\Omega$.
In this case, the s-parameters are given in real/imaginary (RI) form, so use that form in the (.s2p) file.

3) Find the scattering parameters of the 3 dB attenuator circuit given in figure 6. Assume both characteristic and port impedances to be 50Ω.

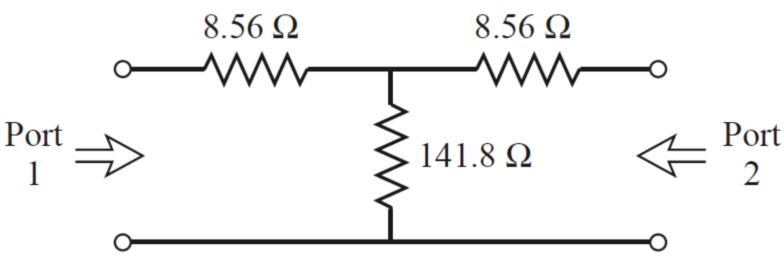

Figure 6: 3-dB Attenuator Circuit

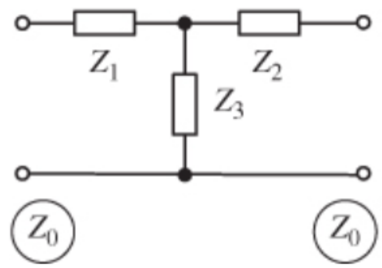

Figure 7: General T-network

(a) Derive the following relations for the general T-network given in figure 7.

$$Z_{in1} = Z_1 + Z_3||(Z_2 + Z_0) = Z_1 + \frac{Z_3(Z_2 + Z_0)}{Z_3 + (Z_2 + Z_0)}$$

$$S_{11} = \frac{Z_{in1} - Z_0}{Z_{in1} + Z_0} = \frac{Z_1Z_2 + Z_1Z_3 + Z_2Z_3 + Z_1Z_0 - Z_2Z_0 - {Z_0}^2}{Z_1Z_2 + Z_1Z_3 + Z_2Z_3 + Z_1Z_0 + Z_2Z_0 + 2Z_3Z_0 + {Z_0}^2}$$

$$S_{22} = \frac{Z_1Z_2 + Z_1Z_3 + Z_2Z_3 - Z_1Z_0 + Z_2Z_0 - {Z_0}^2}{Z_1Z_2 + Z_1Z_3 + Z_2Z_3 + Z_1Z_0 + Z_2Z_0 + 2Z_3Z_0 + {Z_0}^2}$$

$$S_{21} = S_{12} = \frac{2Z_3Z_0}{Z_1Z_2 + Z_1Z_3 + Z_2Z_3 + Z_1Z_0 + Z_2Z_0 + 2Z_3Z_0 + {Z_0}^2}$$

(b) Apply the formulae obtained in part (a) to the circuit in figure 6
- ➢ Calculate the scattering parameters (S_{11}, S_{12}, S_{21}, S_{22})

(c) Show that the output power of the circuit in figure 6 is 3dB less than the input power
(d) Use ADS to simulate the circuit given in figure 6, and compare the result obtained in part (b)

4) A vector network analyzer measures the following reflection coefficient at the input terminals of an antenna:

$$r_A = 0.4e^{-j20^0}$$

The port reference impedance is $Z_0 = 50\Omega$.

(a) Determine the input impedance (Z_A) of the antenna
(b) Validate the result obtained in part (a) using ADS
- ✓ Create a (*.s1p) file with the given s-parameters
- ✓ Perform a one port simulation using S1P element (Start = 1 GHz, Stop = 2 GHz, Step = 100 MHz)
- ✓ Plot the magnitude and phase of reflection coefficient (r_A)
- ✓ Plot the real and imaginary part of input impedance (Z_A)

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5) Figure 8 shows a circuit with disconnected terminals in order to calculate the input impedances and reflection coefficients. Assume the following parameters:

$Z_0 = 50\Omega$ $\quad$ $Z_A = 100\Omega + j\omega L = 100\Omega + j100\Omega$, where L = 15.92 nH $\quad$ $Z = 1/(j\omega C)$, where C = 5 pF

(a) Calculate the impedances Z_{in1} and Z_{in2}
(b) Calculate the reflection coefficients r_1 and r_2

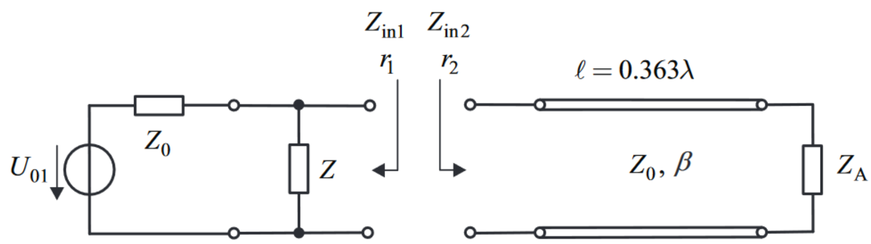

Figure 8: Circuit with Disconnected Terminals

The input impedance Z_{in1} is:

$$Z_{in1} = Z_0 || \frac{1}{j\omega C}$$

The reflection coefficient r_1 is:

$$r_1 = \frac{Z_{in1} - Z_0}{Z_{in2} + Z_0}$$

To determine the reflection coefficient (r_2), first consider the reflection coefficient at the end of the transmission line:

$$r_2' = \frac{Z_A - Z_0}{Z_A + Z_0}$$

The reflection coefficient at the input of the transmission line can be calculated from:

$$r_2 = r_2' e^{-j2\beta l}$$

Use the **Smith-Chart Utility** (selected from Tools menu of ADS) to calculate the input impedance Z_{in2}

(c) Validate the circuit performance using ADS using schematics given in figures 9 and 10
- ➢ Use a frequency range from 0.1 GHz to 2 GHz with stepping of 100 MHz
- ➢ Plot the reflection coefficients (magnitude and phase). Use both rectangular and list plots.
- ➢ Plot the input impedances (real and imaginary part). Use both rectangular and list plots.
- ➢ Use markers to validate the analytical results with simulation results at a frequency of 1 GHz
- ➢ Display the reflection parameters using Smith Chart

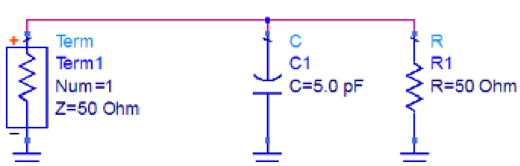

Figure 9: Left Side of Circuit of Figure 8

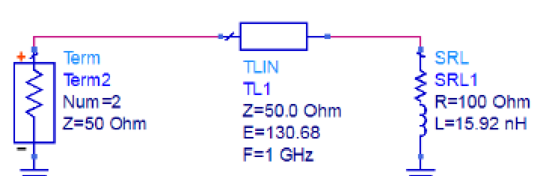

Figure 10:Right Side of Circuit of Figure 8