Universidade Federal do Rio Grande do Norte
Centro de Tecnologia
Departamento de Engenharia Elétrica
ELE0623 - Circuitos para comunicação - 2020.2
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First laboratory: **Transmission lines in ADS**

1 Problem 1

The first problem issues a Low Voltage Differential Signaling line as showed in figure 1. The LVDS technology is a high speed ($> 155.5Mbps$), lower power general purpose interface standard that solves the physical layer bottleneck problems related to higher data rates. According to Texas Instruments "An Overview of LVDS Techonology", its characteristics are:

- LVDS uses differential data transmission that overcomes the problem related to common mode noise in single-ended schemes;
- LVDS features a low voltage swing compared to other industry data transmission standards;
- LVDS uses a constant current mode driver and the transmission media must be terminated to its characteristic impedance to prevent reflections;
- And many others.

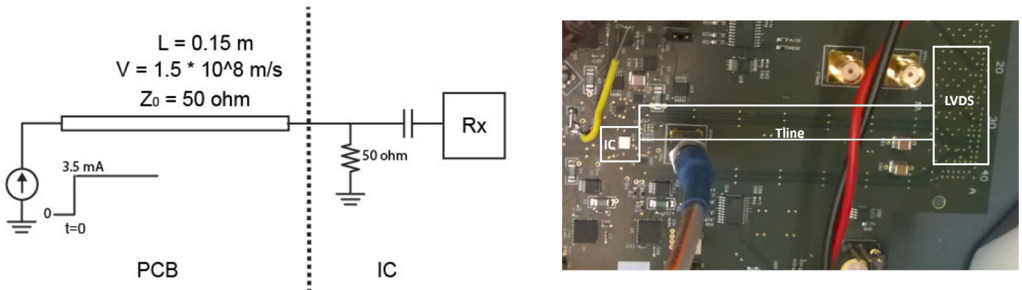


Figure 1: LVDS.

1.1 Load voltage with impedance match

Considering the transmission line in the schematic of figure 1, we can define the load impedance as $Z_L = 50\Omega$ and the line characteristic impedance as $Z_0 = 50\Omega$. The load is matched with the line since their impedance are both equal. This means that any wave travelling from the source will be fully absorbed by the load and therefore there will not be any reflected wave back to the source.

At $t = 0$ the line current is only the parcel of the incident current with value determined by the source step current, so $I = I^+ + I^- = I^+ = 3.5mA$, since it had no time to travel through the line and perhaps be reflected.

The line length is $l = 0.15m$ and the wave propagation velocity in the medium is $v = 1.510^8 m/s$. So the time for any wave to propagate from one end to another of the line is $t = \frac{l}{v} = 1ns$.

The voltage at the source end of the line will see only the line impedance. But the voltage at the load end of the line will only encounter the incident current within one propagation period ($1ns$). So the incident voltage wave will be: $V^+ = Z_L I^+ = 175mV$.

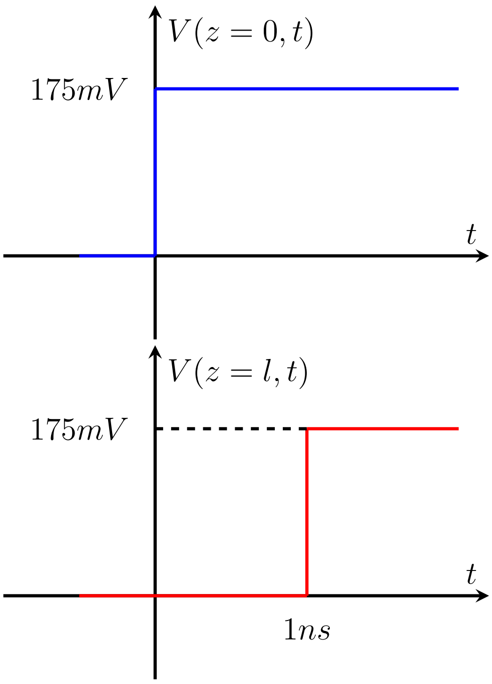


Figure 2: First graph shows the voltage at the start of the line and the second shows the voltage at the end of the line. Source: own.

Once $Z_L = Z_0$, the expression for the reflected voltage wave in equation 1 results in $V^- = 0$. So indeed there is no reflected wave.

$$\frac{V^-}{V^+} = \frac{Z_L - Z_0}{Z_L + Z_0} = \Gamma \tag{1}$$

Simulating the circuit via ADS we easily confirm the theoretical wave forms from the figure 2 by the plot of figure 3

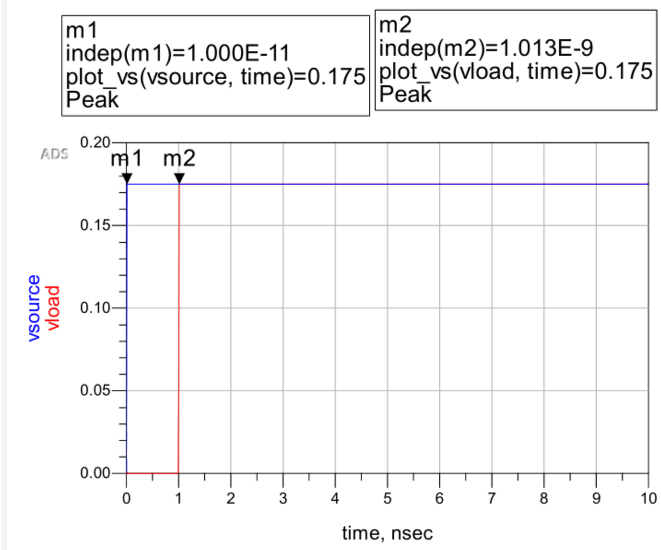


Figure 3: ADS plot of voltage values in each end of the line for: $Z_L = 50\Omega$, $Z_0 = 50\Omega$ and $Z_S = \infty$.

1.2 Steady-state load voltage with impedance mismatch

Considering a characteristic line impedance different from the load impedance ($Z_0 \neq 50\Omega$), according to equation 1 the reflected voltage wave will not be null anymore. Even so evaluating successive reflections in both ends of the line due to the impedance mismatch at a time $t = \infty$ the line will not have effect in the transmission, so the voltage at the load end of the line at $t = \infty$ is: $V(z = l,\ t = \infty) = Z_L I = 50 \times 3.5 \times 10^{-3} = 175mV$.

1.3 Load voltage waveform for $Z_0 = 45\Omega$

To observe the effects of the impedance mismatch in a transient bouncing diagram we can choose $Z_0 = 45\Omega$ and observe the voltage wave at the load end for $t \in [0; 10ns]$. The figure 4 shows the relation between reflected waves and the voltage at each end of the line.

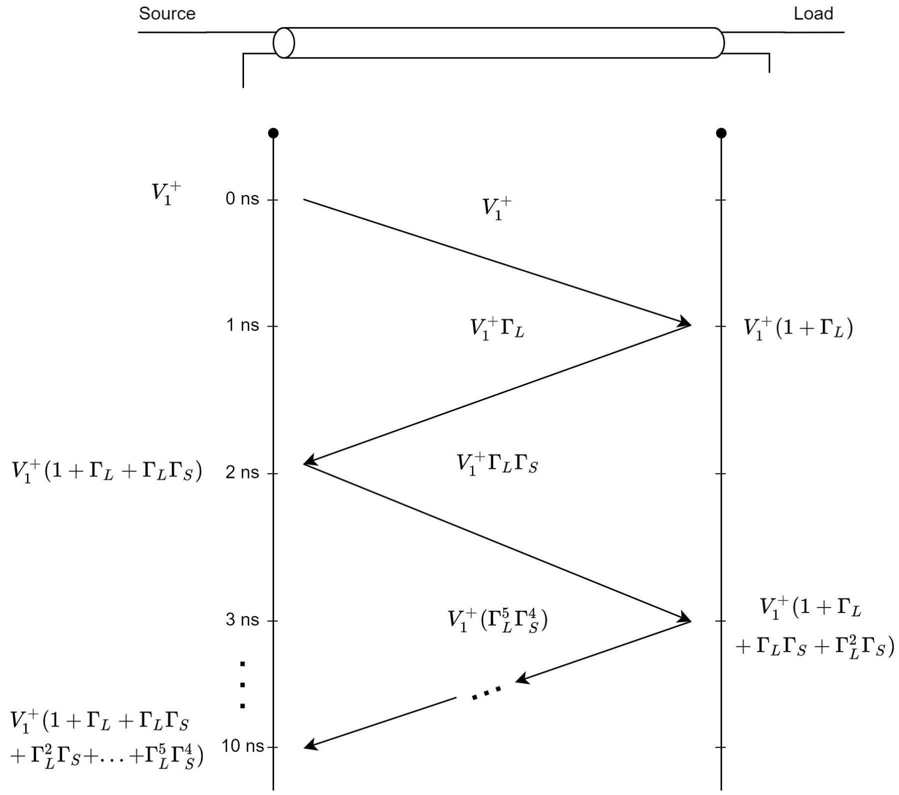


Figure 4: Transient bouncing diagram for $10ns$. Source: own.

Considering the current source as ideal ($Z_s = \infty$), we can derive the expression for the reflection coefficient at the source 2 and also the reflection coefficient at the load with the load and line characteristic impedance 3.

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0} = \frac{1 - \frac{Z_0}{Z_S}}{1 + \frac{Z_0}{Z_S}} = 1 \tag{2}$$

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{50 - 45}{50 + 45} = \frac{1}{19} \tag{3}$$

Calculating all possible values of voltage across the time in each end of the line with the help of the MATLAB script below we obtain the table 1.

```
clc, clear
Z0 = 45;        % characteristic impedance of line [Ohms]
ZL = 50;        % load impedance [Ohms]
t = 0:10;       % time duration [ns]
I = 3.5;        % source current [mA]
VS(1) = Z0*I;   % initial source voltage
VL(1) = 0;      % initial load voltage
gammaL = (ZL-Z0)/(ZL+Z0); % ref. coef. at load
gammaS = 1;               % ref. coef. at source
for i = 2:length(t)
   if(mod(i,2) == 0) % if even index or odd time value
```

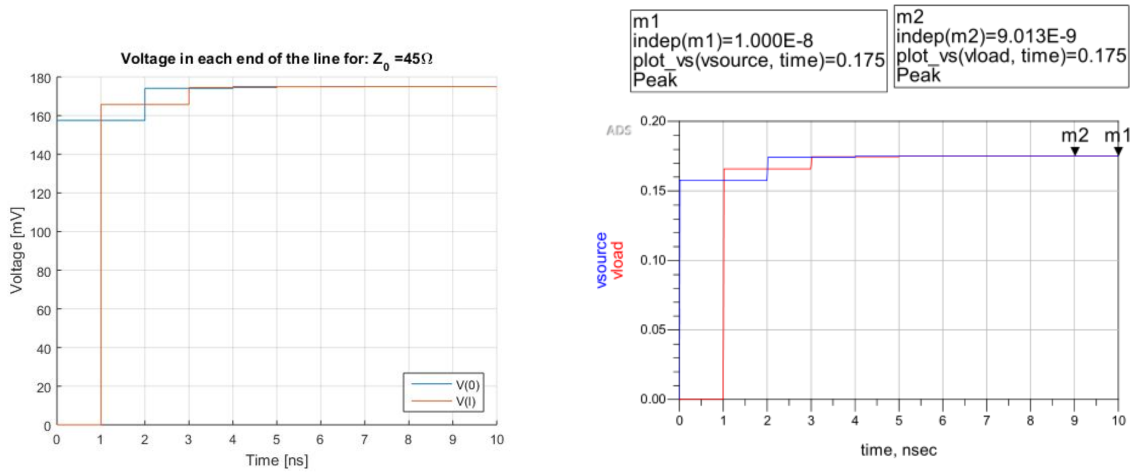
```
        VS(i) = VS(i-1); % keeps previous value
        VL(i) = VS(i-1)+(VS(i-1)-VL(i-1))*gammaL;
    else
        VS(i) = VL(i-1)+(VL(i-1)-VS(i-1))*gammaS;
        VL(i) = VL(i-1); % keeps previous value
    end
end

figure, hold on, stairs(t,VS), stairs(t,VL)
title(strcat('Voltage in each end of the line for: Z_0 = ', num2str(Z0),
     '\Omega'))
legend('V(0)', 'V(l)', 'Location', 'southeast')
xlabel('Time [ns]')
ylabel('Voltage [mV]')
grid on
```

Table 1: Voltage values in each end of the line for: $Z_L = 50\Omega$, $Z_0 = 45\Omega$ and $Z_S = \infty$.

Time [ns]	$V(z=0)$ [mV]	$V(z=l)$ [mV]
0	192,5	0
1	157,5	0
2	157,5	165,79
3	174,08	165,79
4	174,08	174,52
5	174,95	174,52
6	174,95	174,97
7	175	174,97
8	175	175
9	175	175
10	175	175

From the data above, we conclude that even with impedance mismatch between the load and the line, while waiting some time the voltages will come to equilibrium and the load voltage will behave like there is no line impedance at all. The figure 5 extracted from the simulation on ADS illustrates the voltages behavior.



(a) MATLAB (b) ADS

Figure 5: Plot of voltage values in each end of the line (a) MATLAB and (b) ADS for: $Z_L = 50\Omega$, $Z_0 = 45\Omega$ and $Z_S = \infty$.

1.4 Load voltage waveform for $Z_0 = 55\Omega$

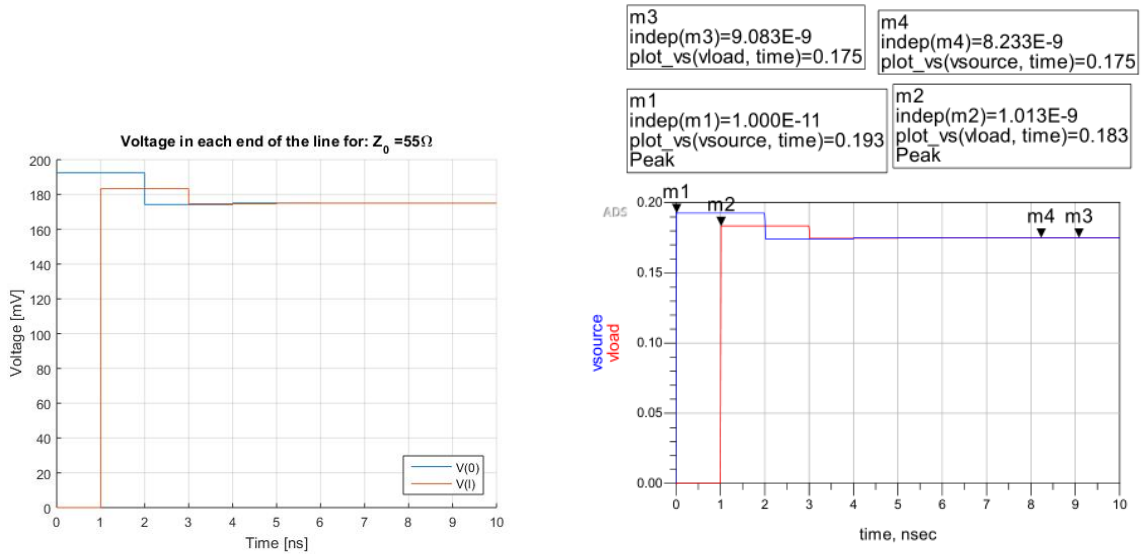
Another test proposes to change the line characteristic impedance to $Z_0 = 55\Omega$. Regarding the reflection coeficients, the only one that will change is the one related to the load, so:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{50 - 55}{50 + 55} = -\frac{1}{21} \tag{4}$$

The same figure 4 of the bouncing diagram and the MATLAB code can be reused (it needs to change de Z_0 value in the code).

Table 2: Voltage values in each end of the line for: $Z_L = 50\Omega$, $Z_0 = 55\Omega$ and $Z_S = \infty$.

Time [ns]	$V(z = 0)$ [mV]	$V(z = l)$ [mV]
0	192,5	0
1	192,5	0
2	192,5	183,33
3	174,17	183,33
4	174,17	174,6
5	175,04	174,6
6	175,04	175,02
7	175	175,02
8	175	175
9	175	175
10	175	175



(a) MATLAB (b) ADS

Figure 6: Plot of voltage values in each end of the line (a) MATLAB and (b) ADS for: $Z_L = 50\Omega$, $Z_0 = 55\Omega$ and $Z_S = \infty$.

The results showed in the table 2 and graphically in the figure 6 allow us to see the effects of the risen in the line characteristic impedance above the load impedance value. The direct effect is an overshoot in the voltage value. Despite this, the voltage values tend to equilibrium just like the previous experiment.

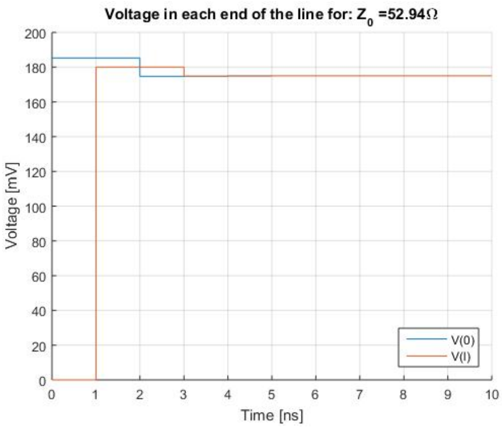
1.5 Maximum overshoot tolerance in load voltage

Now considering a receptor input polarized with $1V$ and maximum voltage tolerable of $1.18V$. In the previous topic we have seen that a line characteristic impedance higher than the load impedance provokes a overshoot in the voltage on both ends of the line. The highest peak occurs when the first reflection occurs. So we have to figure it out which value of Z_0 guarantees a max. voltage deviation of $0.18V$.

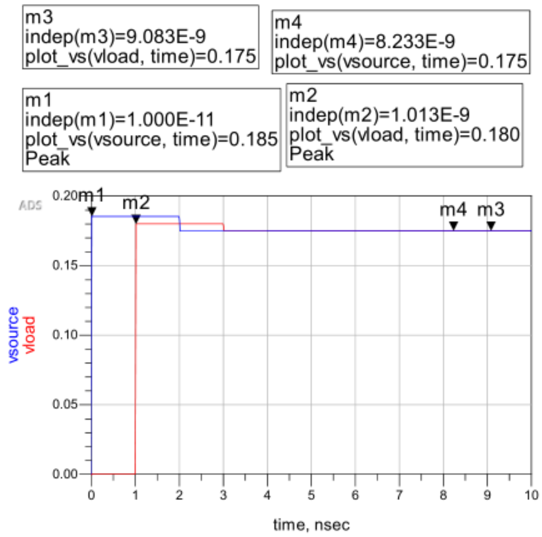
$$\begin{gathered} V_1^+ + V_1^- < \delta_V \\ IZ_0(1+\Gamma_L) < \delta_V \\ IZ_0\left(1+\frac{Z_L - Z_0}{Z_L + Z_0}\right) < \delta_V \end{gathered}$$

$$Z_0 < \frac{\delta_V Z_L}{2IZ_L - \delta_V} \tag{5}$$

So according to equation 5 for a voltage deviation of $\delta_V = 180mV$, we can observe that the max. value for the line characteristic impedance is $Z_0 = 52.94\Omega$. We have obtained the results in the plot of figure 7 that compares the theoretical value in MATLAB with the corresponding simulation on ADS (without the polarization of $1V$).



(a) MATLAB



(b) ADS

Figure 7: Plot of voltage values in each end of the line (a) MATLAB and (b) ADS for: $Z_L = 50\Omega$, $Z_0 = 52.94\Omega$ and $Z_S = \infty$.

2 Problem 3

This problem takes into account the transmission line in figure 8. The circuit illustrates a power amplifier (non-ideal voltage source with impedance Z_S) that feeds an antenna (load) with impedance $Z_L = 50\Omega$ through a transmission line with characteristic impedance $Z_0 = 50\Omega$, length $l = 21.875cm$ and relative permittivity of $\epsilon_r = 4$ (the relative permeability is considered to be unitary $\mu_r = 1$). Additional information was achieved from measurements with a capacitive probe, they are:

- As getting far from the load the voltage drops and reach a minimum at $4.75mm$ of distance from the antenna;
- Beyond this point the voltage rises and reach its maximum at $36mm$ of distance from the antenna with VSWR = 3.

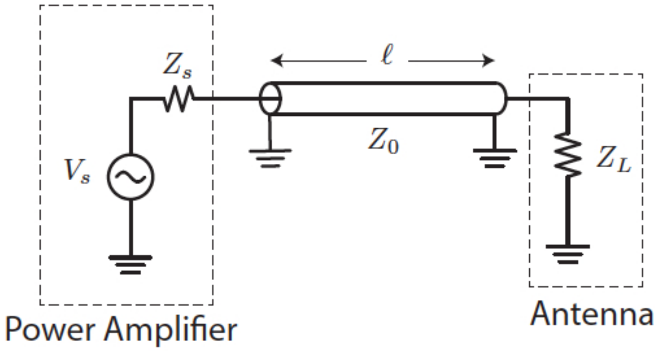


Figure 8: Transmission line for problem 3.

2.1 Power amplifier operating frequency

It known that the distance between the maximum voltage and its minimum is equivalent to a quarter of wavelength, so: $\Delta z = z_{max} - z_{min} = \frac{\lambda}{4} = 31.25mm$ and finally $\lambda = 125mm$. Therefore the operating frequency is given by equation 6:

$$f = \frac{v}{\lambda} = \frac{c}{\lambda}\frac{1}{\sqrt{\epsilon_r \mu_r}} = \frac{3 \times 10^8}{125 \times 10^{-3}}\frac{1}{\sqrt{4 \times 1}} = 1.2GHz \tag{6}$$

2.2 Antenna impedance at operating frequency

The impedance in any given point of the line is given by the equation 7.

$$Z(z) = Z_0 \frac{1 + \rho_L e^{2j\beta z}}{1 - \rho_L e^{2j\beta z}} \tag{7}$$

Considering that the antenna is located at $z = 0$, the exponential term turn to be $e^{2j\beta z} = 1$ and the equation 7 becomes 8.

$$Z_L = Z_0 \frac{1 + \rho_L}{1 - \rho_L} \tag{8}$$

Although the reflection coefficient ρ_L remains unknown and it has a module and phase ($\rho_L = |\rho_L| e^{j\theta}$). Its module can be computed by the equation 9 while the phase can be found by the equation 10 that relate it with the distance whose occurs a voltage minimum.

$$\text{VSWR} = \frac{1 + |\rho_L|}{1 - |\rho_L|} \Rightarrow |\rho_L| = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \tag{9}$$

$$z_{max} = \frac{\theta\lambda}{4\pi} \Rightarrow \theta = \frac{4\pi z_{max}}{\lambda} \tag{10}$$

For $\text{VSWR} = 3$, implies $|\rho_L| = 0.5$ and bearing in mind the results from the previous section, we have the phase $\theta = 3.6191rad$. Therefore $\rho_L = 0.5e^{j3.6191}$ and regarding the equation 8, finally $Z_L = 20.569e^{-j0.5497}\Omega = 17.538 - j10.74\Omega$.

Plotting the voltage waveform (figure 9) in both end of the line we observed that indeed the VSWR is 3.

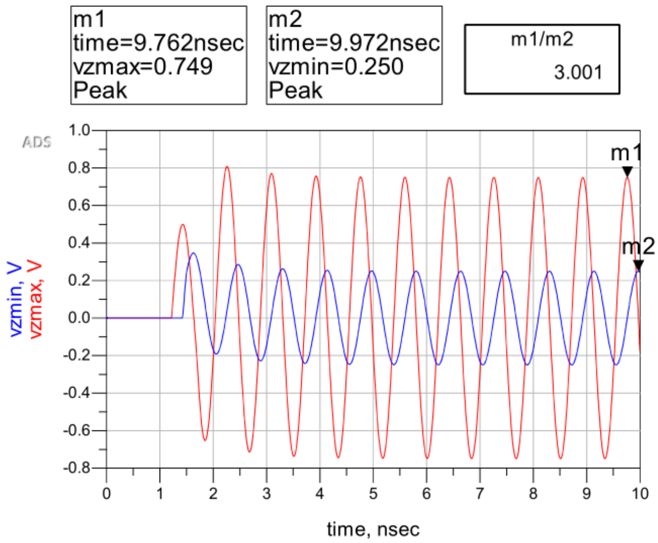


Figure 9: Voltage at source and load with sinusoidal excitation.

2.3 Mathematical expression of voltage along the line

Considering a lossless line ($\alpha = 0$), the voltage along the line takes the form:

$$V(-z) = V^+e^{-\gamma z} + V^-e^{+\gamma z}$$
$$V(-z) = V^+e^{-j\beta z} + V^-e^{+j\beta z}$$

$$V(-z) = V^+e^{+j\beta z}(1 + \rho_L e^{-2j\beta z}) \tag{11}$$

At the source ($z = l$) the previous expression becomes as follow (also the voltage provided by the source is the one after the voltage drop at the source impedance):

$$V(-l) = V^+e^{+j\beta l}(1 + \rho_L e^{-2j\beta l}) = V_S - Z_S I_S \tag{12}$$

While the source current is the composition of the incident and reflected current:

$$I_S = I^+(-l) + I^-(-l) = \frac{V^+(-l) + V^-(-l)}{Z_0}$$

The expression 12 becomes:

$$V(-l) = \frac{V^+e^{+j\beta l}}{Z_0}(1 - \rho_L e^{+2j\beta l})$$

Then:

$$V^+ = V_S e^{-j\beta l}[(1 + \rho_L e^{-2j\beta l}) + \frac{Z_S}{Z_0}(1 - \rho_L e^{-2j\beta l})]^{-1} \tag{13}$$

Once V^+ is a known value, the expression 11 will allow us to trace the voltage envelope with a variable z that will limit the voltage at any point and any time of the line.

The mathematical expression for the voltage along the line was derived in the Display Window environment of ADS, resulting in the figure 10. Once the variables were stored in the ADS work space, the waveform from figure 11 could be plotted, resulting in the combination of the upper and lower voltage envelope due to the stationary wave and the voltage waveform across the line in a given time (selected in a slider) bounded inside the envelope. Even varying the time instant of analysis, the voltage still bounded inside the envelope across all line.

Figure 10: Set of equations in the Display Window environment of ADS.

Vz	z
0.731 / -170.962	-0.219
0.745 / -168.819	-0.217
0.750 / -166.730	-0.214
0.748 / -164.648	-0.212

Vplus	mag(Vplus+rhoL*Vplus)	Vl
0.50000 / 90.00000	0.30057	0.73133 / -170.96202

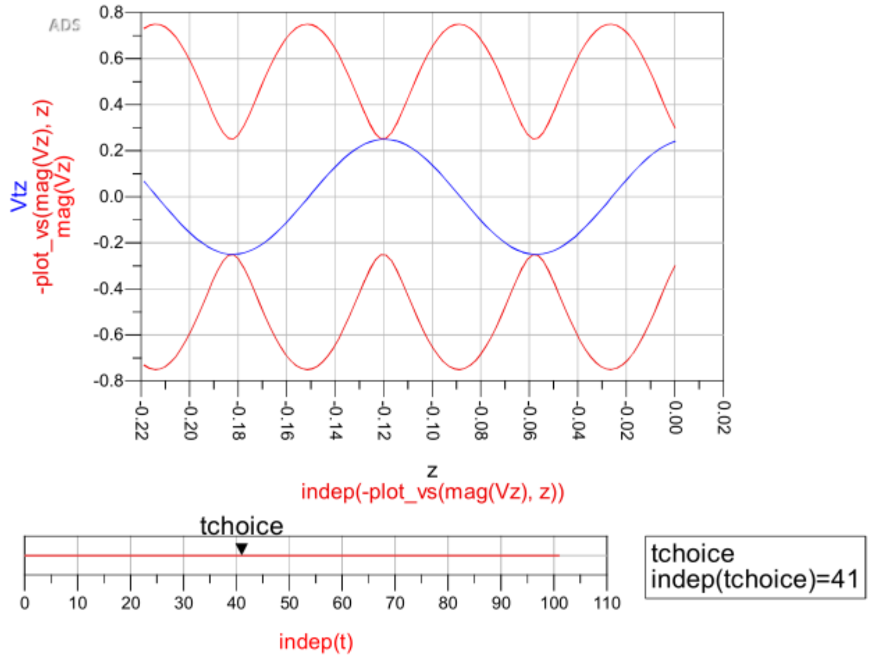


Figure 11: Waveform for the voltage along the line.