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Scattering-Parameter Analysis of High-Speed Interconnects Using a Two-Port Network

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Abstract— High-speed interconnects cannot always be treated as ideal wires because signal propagation, impedance mismatch, attenuation, and discontinuities affect signal quality. This article presents a two-port network approach for analyzing high-speed interconnects using scattering parameters. The four parameters, S_{11} , S_{12} , S_{21} , and S_{22} , are explained in terms of input reflection, reverse transmission, forward transmission, and output reflection. A practical simulation using a $50\ \Omega$ transmission line and different load impedances demonstrates the effect of impedance mismatch on signal reflection.

Keywords— S-parameters, two-port network, high-speed interconnects, signal integrity, impedance matching, reflection coefficient, transmission line, insertion loss

I. INTRODUCTION

At low frequencies, an electrical wire is often treated as an ideal connection between two points. This approximation becomes inaccurate when signals contain high-frequency components or have very fast rise and fall times. At such speeds, the physical length, characteristic impedance, propagation delay, and losses of an interconnect begin to influence the transmitted waveform.

A printed-circuit-board trace, cable, connector, or package can therefore behave as a transmission-line structure rather than a simple wire. Impedance discontinuities may produce reflected signals, while conductor and

dielectric losses may reduce the signal amplitude.

Engineers analyze these effects by representing the interconnect as a network with an input port and an output port. Scattering parameters provide a convenient way to describe the relationship between incident and outgoing waves at these ports.

II. DETAILED EXPLANATION

A. HIGH-SPEED INTERCONNECTS

An interconnect is the physical path through

which an electrical signal travels. Examples include printed-circuit-board traces, coaxial cables, connectors, and flexible cables.

At high frequencies, an interconnect has distributed resistance, inductance, capacitance, and conductance. It must therefore be treated as a transmission line rather than as an ideal wire.

When a signal is applied to a transmission line, the electrical effect does not appear at every point of the line instantly. The signal travels along the line at a finite speed called the **propagation velocity**. It depends mainly on the inductance and capacitance distributed along the line. It is defined as

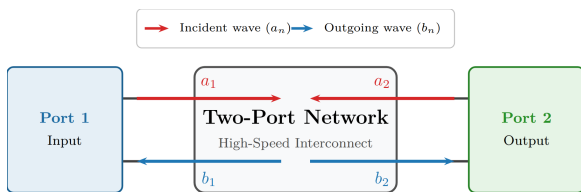
$$v_p = \frac{1}{\sqrt{L'C'}} \quad (1)$$

where L' is the inductance per unit length and C' is the capacitance per unit length.

Impedance is the total opposition that a circuit presents to the flow of an alternating electrical signal. A transmission line, such as a high-speed PCB trace, coaxial cable, or connector, has a special type of impedance called **characteristic impedance**. It is the impedance that a travelling signal experiences as it moves along the transmission line. It is represented by Z_0 and is measured in ohms.

$$Z_0 = \sqrt{\frac{L'}{C'}} \quad (2)$$

B. TWO-PORT NETWORK AND SCATTERING PARAMETERS



Scattering parameters describe reflected and transmitted waves.

Figure 1: Two-port representation of a high-speed interconnect showing incident and outgoing waves.

A high-speed interconnect can be represented

as a two-port network. A port is a pair of terminals through which an electrical signal enters or leaves a network. Port 1 is the input port, connected to the signal source, while Port 2 is the output port, connected to the load. The region between the two ports represents the high-speed interconnect.

At Port 1, a_1 represents the incident wave entering the network and b_1 represents the outgoing wave leaving the network towards the source. At Port 2, a_2 represents the incident wave entering the network from the output side and b_2 represents the outgoing wave travelling towards the load.

The relationship between the incident and outgoing waves is described by the scattering-parameter matrix:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad (3)$$

The expanded equations are

$$b_1 = S_{11}a_1 + S_{12}a_2, \quad (4)$$

$$b_2 = S_{21}a_1 + S_{22}a_2. \quad (5)$$

Each S-parameter is obtained by exciting one port while terminating the other port with its reference impedance.

The input reflection coefficient is

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \quad (6)$$

It represents the fraction of the incident wave at Port 1 that is reflected back towards the source. A small magnitude of S_{11} indicates good input matching.

The forward transmission coefficient is

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \quad (7)$$

It represents the signal transmitted from Port 1 to Port 2. A large magnitude of S_{21} indicates good forward transmission through the interconnect.

The reverse transmission coefficient is

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} \quad (8)$$

It represents the signal transmitted from Port 2 back to Port 1. For a reciprocal network, $S_{12} = S_{21}$.

The output reflection coefficient is

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} \quad (9)$$

It represents the fraction of the wave incident at Port 2 that is reflected back from the output side. A small magnitude of S_{22} indicates good output matching.

C. SIGNAL REFLECTION

When a signal travels through a transmission line, it expects to see the characteristic impedance Z_0 of the line. If the load impedance Z_L is different from Z_0 , the signal cannot transfer completely into the load. A portion of the signal is reflected back towards the source. This condition is called **impedance mismatch**.

The reflection coefficient at the load is

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (10)$$

If the load is matched to the transmission line,

$$Z_L = Z_0 \quad (11)$$

then $\Gamma_L = 0$ according to **Maximum Power Transfer** principle. The maximum power is transferred to the load without any signal reflection. If Z_L is different from Z_0 , the magnitude of Γ_L becomes greater than zero, indicating that some signal energy is reflected.

For example, consider a transmission line with $Z_0 = 50 \Omega$. A 50Ω load is matched to the line and produces no reflection. However, a 75Ω or 25Ω load produces a reflected signal. A severe mismatch can cause overshoot, undershoot, ringing, and distortion in the received waveform.

D. ATTENUATION, INSERTION LOSS AND RETURN LOSS

As a signal travels through an interconnect, its amplitude gradually decreases. This reduction in signal strength is called **attenuation**. Attenuation occurs because some of the signal energy is converted into heat or absorbed by the dielectric material surrounding the conductor. Conductor resistance, skin effect, dielectric loss, and connector losses all contribute to attenuation.

Attenuation is commonly observed through the forward transmission parameter S_{21} . A reduction in the magnitude of S_{21} indicates that the interconnect has reduced the transmitted signal.

Insertion loss describes the reduction in signal power caused by inserting a device or interconnect between a source and a load. It is commonly expressed using the forward transmission parameter S_{21} :

$$IL = -20 \log_{10} |S_{21}| \text{ dB} \quad (12)$$

For a passive interconnect, $|S_{21}| \leq 1$. A smaller insertion loss indicates better signal transmission. For example, if $|S_{21}| = 1$, the insertion loss is 0 dB, representing ideal transmission. If $|S_{21}| = 0.5$, then

$$IL = -20 \log_{10}(0.5) \approx 6.02 \text{ dB} \quad (13)$$

The Return Loss measures how much signal is reflected back towards the source because of impedance mismatch and is related to the reflection coefficient Γ_L . A larger return loss value indicates better matching and less reflected signal.

$$RL = -20 \log_{10} |\Gamma_L| \text{ dB} \quad (14)$$

This indicates a reduction in the transmitted signal level. Therefore, impedance mismatch produces reflected signals, attenuation reduces signal amplitude during propagation, and insertion loss measures the reduction in forward transmission.

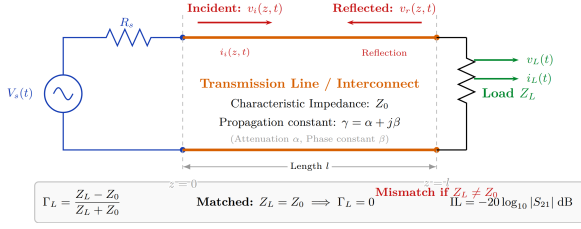


Figure 2: Transmission-line circuit showing incident, reflected, and transmitted signals under impedance-matching and impedance-mismatch conditions.

IV. PROGRAMMING EXAMPLE

A. OBJECTIVE OF EXPERIMENT

The objective of this experiment is to study the effect of load impedance on the reflection coefficient of a transmission line. A transmission line with a characteristic impedance of $Z_0 = 50 \Omega$ is considered, and different load impedances are connected to its end. The selected load values are: $Z_L = 25 \Omega, 50 \Omega, 75 \Omega, 100 \Omega$

B CIRCUIT DIAGRAM

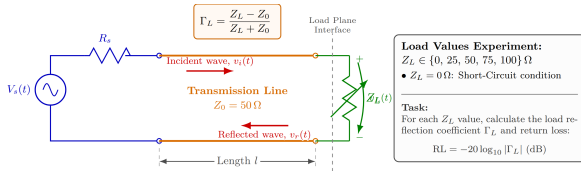


Figure 3: Circuit setup with variable load.

C MATLAB DEMONSTRATION OF THE EXPERIMENT

Listing 1: MATLAB code for reflection coefficient and return loss

```

1 clc;
2 clear;
3 close all;
4
5 % Characteristic impedance
6 Z0 = 50;
7
8 % Load impedance values
9 ZL = [0 25 50 75 100];

```

```

11 % Reflection coefficient
12 Gamma = (ZL - Z0) ./ (ZL + Z0);
13
14 % Magnitude of reflection coefficient
15 GammaMag = abs(Gamma);
16
17 % Return loss
18 % eps avoids log10(0) for the matched 50-ohm load
19 ReturnLoss = -20 * log10(max(GammaMag,
20 eps));
21
22 % Display values
23 disp('ZL      Gamma      |Gamma|
24      Return Loss (dB)')
25 disp([ZL.' Gamma.' GammaMag.' ReturnLoss
26 .'])
27
28 % Create two graphs
29 figure;
30
31 % Graph 1: Load impedance versus Gamma
32 subplot(1,2,1)
33 plot(ZL, Gamma, 'bo-', 'LineWidth', 2)
34 grid on
35 xlabel('Load impedance Z_L (\Omega)')
36 ylabel('Reflection coefficient \Gamma_L')
37 title('Z_L vs \Gamma_L')
38
39 % Graph 2: Gamma magnitude versus return loss
40 subplot(1,2,2)
41 plot(GammaMag, ReturnLoss, 'go-', '
42 LineWidth', 2)
43 grid on
44 xlabel('| \Gamma_L |')
45 ylabel('Return loss (dB)')
46 title('| \Gamma_L | vs Return Loss')
47
48 % Save the figure
49 saveas(gcf, 'reflection_return_loss.png')

```

D MATLAB RESULTS AND DISCUSSION

Table 1: Reflection coefficient and return loss for different load impedances

$Z_L (\Omega)$	Γ_L	$ \Gamma_L $	Return Loss (dB)
0	-1.0000	1.0000	0.00
25	-0.3333	0.3333	9.54
50	0.0000	0.0000	∞
75	0.2000	0.2000	13.98
100	0.3333	0.3333	9.54

Table 1 shows the calculated reflection coefficient, its magnitude, and return loss for different load impedances. When $Z_L = 50 \Omega$, the load is matched to the 50Ω transmission line. Therefore, $\Gamma_L = 0$, indicating that no signal is reflected and the theoretical return loss is infinite. The 0Ω load represents a short-circuit condition and produces complete reflection with $\Gamma_L = -1$.

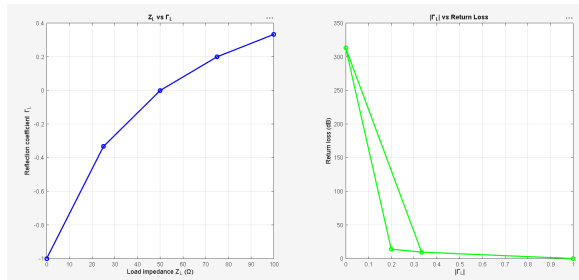


Figure 4: Reflection coefficient versus load impedance and return loss versus the magnitude of the reflection coefficient.

The graph shows how the load impedance affects signal reflection in a transmission line. When the load impedance is equal to the characteristic impedance of 50Ω , there is no mismatch, so the reflection coefficient is zero and the theoretical return loss is infinite. In the MATLAB calculation, the program uses `eps`, which is a very small numerical value, instead of zero to avoid the undefined logarithm of zero. This is why the matched 50Ω condition appears with a very large return-loss value of approximately 313.07 dB in the output. This value is only a numerical representation and

should not be interpreted as the actual physical return loss; ideally, it is infinite. When the load impedance differs from 50Ω , part of the signal is reflected back towards the source, resulting in a finite return-loss value.

V. CONCLUSION

A high-speed interconnect should not always be treated as an ideal wire. Impedance mismatch causes reflection, while conductor and dielectric losses reduce the transmitted signal. A two-port network and its S-parameters provide a systematic method for analyzing these effects and improving signal integrity.

VI. REFERENCES

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