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S-Parameters Extraction of a Desired Network with Time-Domain Gates

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Abstract—A method for extracting a desired network from the composite measurement of a desired and undesired networks combination is proposed. The desired network is required to be a reciprocal and passive network. Time-domain responses are chosen by time-domain gates according to the signal flow diagram of the measured networks. This method can be used to characterize fixtures and de-embed of fixtures effects from the composite measurement of a device under test (DUT) and fixtures combination. This method can also compensate for masking errors. Extraction for the S-parameters of the desired network are described in detail, and the extraction result is validated with two simulations.

1. INTRODUCTION

A raw measurement obtained from a vector network analyzer (VNA) often is a composite measurement of the device under test (DUT) and the fixture. The DUT is a desired network for the measurement. The fixture has an effect on the DUT measurement and is an undesired network in the measurement. It is important to extract S-parameters of the desired network and remove the effects of the undesired network from the raw measurement. There are many methods to extract S-parameters and improve the measurement accuracy of the desired network.

The de-embedding of undesired fixtures is a common method to remove the effect of fixtures from the composite measurement of the DUT and fixtures. It is important to obtain the characterization of fixtures. Some of the characterization methods need to construct a model for a fixture [1, 2]. These models have high accuracy for simple structures and need modification with a change of frequency range. Calibration SOLT and TRL are well known [3, 4], but these need a well-designed calibration kit. A time-domain channel characterization (TCC) is also a choice to obtain the characterization of fixtures [5, 6], but the fixtures need to be symmetric.

A time-domain gate can be used to extract the desired part of the DUT [7]. Time-domain gated responses sometimes contain masking error and the masking network needs to be known to compensate for the error. Masking error occurs when the response of one discontinuity affects or obscures the response of subsequent discontinuities in the circuit.

This paper propose a method to extract the desired network S-parameters from the raw measurement by using a time-domain gate. The time-domain gate is used to choose time-domain responses according to the signal flows of the measured circuit and the S-parameters of the desired network are extracted from the time-domain gated responses. The desired network needs to be reciprocal and passive. This method can be used to compensate the masking errors and characterize the fixtures.

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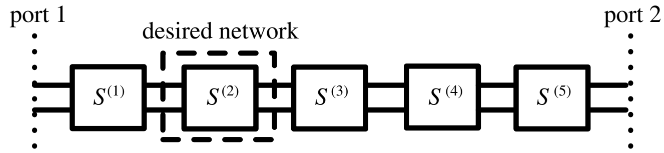

Figure 1. A measured circuit consists of five cascading networks.

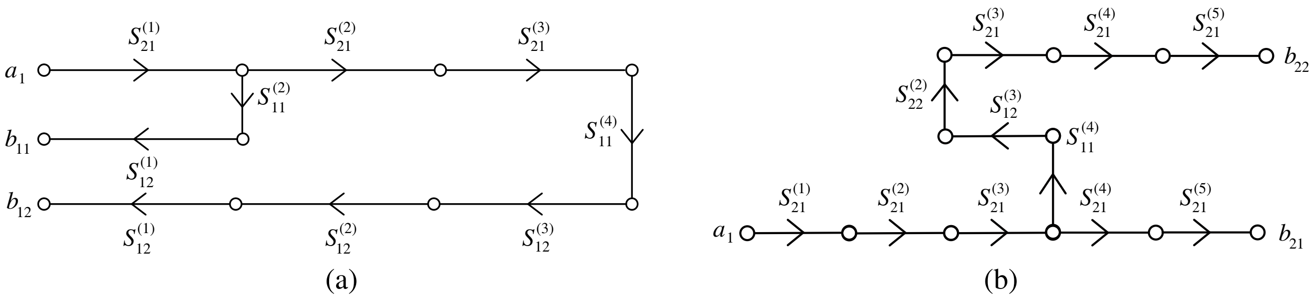

Figure 2. Signal flow diagram based on the circuit of Fig. 1. (a) Signal flow diagram of reflection coefficients. (b) Signal flow diagram of transmission coefficients.

2. THEORY

The measured circuit shown in Fig. 1 is composed of five cascading networks characterized by the scattering matrices $S^{(k)}$. Port 1 and Port 2 are the measurement reference planes. Networks 1, 3 and 5 are transmission lines that are interrupted by discontinuities — networks 2 and 4.

Network 2 is the desired measured network and its S-parameters can't be directly extracted from S-parameters measured by a VNA. The algorithm for extracting S-parameters of the desired network from the raw measurements is detailed below.

2.1. Calculate the Magnitude of the S-Parameters

A signal flow diagram for the measured circuit is shown in Fig. 2. a_1 represents incoming waves from port 1. b_{11} and b_{12} are reflected waves from different routes at port 1. Similarly, b_{21} and b_{22} are transmission waves at port 2. We can infer Eq. (1) from Fig. 2 (It is necessary to know the S-parameters dependence on frequency [8], some equations in this paper don't include this discussion for brevity).

$$\begin{cases} S_{11(1)} = \dfrac{b_{11}}{a_1} = S_{21}^{(1)} S_{11}^{(2)} S_{12}^{(1)}, \\ S_{11(2)} = \dfrac{b_{12}}{a_1} = S_{21}^{(1)} S_{21}^{(2)} S_{21}^{(3)} S_{11}^{(4)} S_{12}^{(3)} S_{12}^{(2)} S_{12}^{(1)}, \\ S_{21(1)} = \dfrac{b_{21}}{a_1} = S_{21}^{(1)} S_{21}^{(2)} S_{21}^{(3)} S_{21}^{(4)} S_{21}^{(5)}, \\ S_{21(2)} = \dfrac{b_{22}}{a_1} = S_{21}^{(1)} S_{21}^{(2)} S_{21}^{(3)} S_{11}^{(4)} S_{12}^{(3)} S_{22}^{(2)} S_{21}^{(3)} S_{21}^{(4)} S_{21}^{(5)}. \end{cases} \tag{1}$$

$S_{ij}^{(m)}$ is the scattering parameter of network m. $S_{11(1)}$ and $S_{11(2)}$ are two independent reflection coefficients that are a part of S_{11}. $S_{21(1)}$ and $S_{21(2)}$ are two independent transmission coefficients that are also a part of S_{21}. These coefficients satisfy:

$$\begin{cases} S_{11}(f) = \displaystyle\sum_{i=1}^{\infty} S_{11(i)}(f), \\ S_{21}(f) = \displaystyle\sum_{i=1}^{\infty} S_{21(i)}(f). \end{cases} \tag{2}$$

where $S_{11}(f)$ and $S_{21}(f)$ are the original measurements of the reflection and transmission coefficients by a VNA. $S_{11(i)}(f)$ is a part of $S_{11}(f)$, and $S_{21(i)}(f)$ is a part of $S_{21}(f)$.

In order to extract $S_{11(i)}(f)$ from $S_{11}(f)$, the reflection response $s_{11}(t)$ in the time domain is calculated using the inverse Fourier transform [9]:

$$s_{11}(t) = \hat{F}^{-1} S_{11}(f) = \hat{F}^{-1} \sum_{i=1}^{\infty} S_{11(i)}(f) = \sum_{i=1}^{\infty} s_{11(i)}(t). \tag{3}$$

$\hat{F}^{-1}$ is the inverse Fourier transform operation. The reflection response $s_{11(i)}(t)$ corresponds to $S_{11(i)}(f)$.

Figure 3 shows a time domain reflection response. If the impulses of the time domain response do not overlap then $s_{11(1)}(t)$ can be extracted by a time-domain gate function [10]:

$$s_{11(1)}(t) = s_{11}(t) \quad \text{as} \quad t_1 \le t \le t_2 \tag{4}$$

Applying the Fourier transform, its corresponding frequency domain response $S_{11(1)}(f)$ can be obtained. Repeating similar steps, it is easy to obtain $S_{11(2)}(f)$, $S_{21(1)}(f)$, and $S_{21(2)}(f)$. Thus Eq. (5) can be calculated based on these partial S-parameters:

$$\frac{S_{11(2)} S_{21(1)}}{S_{11(1)} S_{21(2)}} = \frac{S_{12}^{(2)} S_{21}^{(2)}}{S_{11}^{(2)} S_{22}^{(2)}} = \frac{\left(S_{12}^{(2)}\right)^2}{S_{11}^{(2)} S_{22}^{(2)}} = C_0 e^{j\phi_0}. \tag{5}$$

where C_0 and ϕ_0 are the magnitude and phase of the ratio among the time-domain gated S-parameters. Because the desired network 2 is required to be lossless and reciprocal, its S-parameters satisfy:

$$\begin{cases} S_{12}^{(2)} = S_{21}^{(2)}, \\ \left|S_{11}^{(2)}\right| = \left|S_{22}^{(2)}\right|. \end{cases} \tag{6}$$

Combining Eq. (5) and Eq. (6), the amplitude of the desired network S-parameters can be inferred:

$$\begin{cases} \left|S_{11}^{(2)}\right| = \left|S_{22}^{(2)}\right| = \sqrt{1/(1 + C_0)}, \\ \left|S_{12}^{(2)}\right| = \left|S_{21}^{(2)}\right| = \sqrt{C_0/(1 + C_0)}. \end{cases} \tag{7}$$

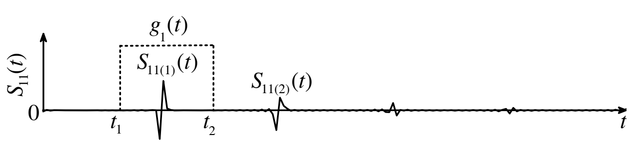

Figure 3. Reflection response in the time domain.

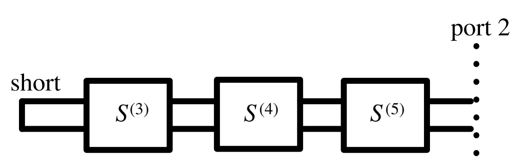

Figure 4. A short circuit that is built for $\theta_{22}^{(2)}$.

2.2. Calculate the Phase of the S-Parameters

According to Eq. (5), it can be inferred:

$$2\theta_{12}^{(2)} - \theta_{11}^{(2)} - \theta_{22}^{(2)} = \phi_0. \tag{8}$$

where $\theta_{11}^{(2)}$, $\theta_{12}^{(2)}$, and $\theta_{22}^{(2)}$ are the phases of $S_{11}^{(2)}$, $S_{12}^{(2)}$ and $S_{22}^{(2)}$.

Network 1 is a transmission line, and its electrical length can be obtained from the time response $s_{11(1)}(t)$. The phase of $S_{12}^{(1)}$ can be calculated according to its electrical length. Combining the phase of $S_{12}^{(1)}$ and $S_{11(1)}(f)$, the $\theta_{11}^{(2)}$ can be found.

If $\theta_{12}^{(2)}$ is required to be calculated, then $\theta_{22}^{(2)}$ needs to be calculated first. In order to infer $\theta_{12}^{(2)}$, a short circuit shown in Fig. 4 is built and its signal flow diagram is shown in Fig. 5.

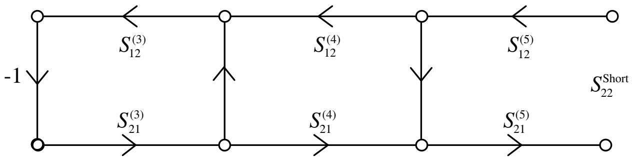

Figure 5. Signal flow diagram for short circuit.

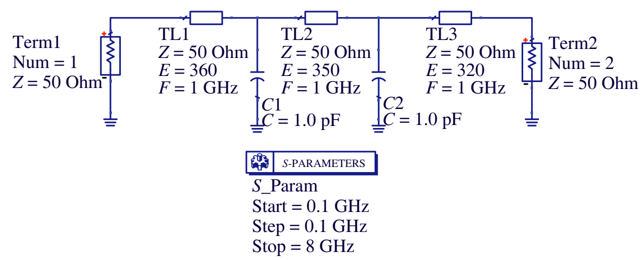

Figure 6. A test circuit where $C1$ is a undesired part of the measurement.

From Mason's rule [11], we can know the relations of the short circuit S-parameters and time-domain gated responses:

$$S_{22}^{\text{Short}} = S_{22(1)} - S_{22(2)} / \left(S_{22}^{(2)} + S_{21(2)} / S_{21(1)} \right). \tag{9}$$

S_{22}^{Short} is the reflection parameter of the short circuit at the composite network input. The S-parameters $S_{22(1)}$ and $S_{22(2)}$ are time-domain gated responses and they can be extracted from $S_{22}(f)$ of the measured circuit in Fig. 1. So the phase $\theta_{22}^{(2)}$ can be inferred from $S_{22}^{(2)}$:

$$S_{22}^{(2)} = S_{22(2)} / (S_{22(1)} - S_{22}^{\text{Short}}) - S_{21(2)} / S_{21(1)}. \tag{10}$$

$\theta_{12}^{(2)}$ can be found by combining $\theta_{11}^{(2)}$, $\theta_{22}^{(2)}$ and Eq. (8). All the phases of network 2 S-parameters can now be calculated.

3. EXPERIMENTAL SETUP AND RESULTS

In order to introduce the method of extracting the desired network characterization from the raw measurements, two simulation experiments are described below.

3.1. Compensate for the Masking Error

The raw measurements are the S-parameters of the DUT as shown in Fig. 6. The capacitance $C1$ is an undesired network in the DUT, and its effect needs to be removed from the measurements.

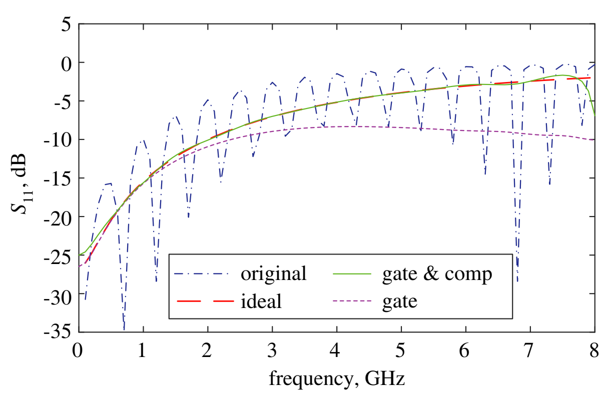

Figure 7. Comparison of reflection parameters from raw measurements (blue trace), time domain gated measurements (purple trace), time-domain gated and compensated measurements (green trace), and the DUT without undesired network (red trace).

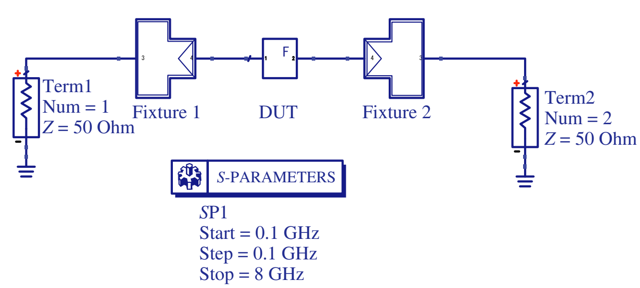

Figure 8. Schematic of the composition of a DUT and fixtures combination.

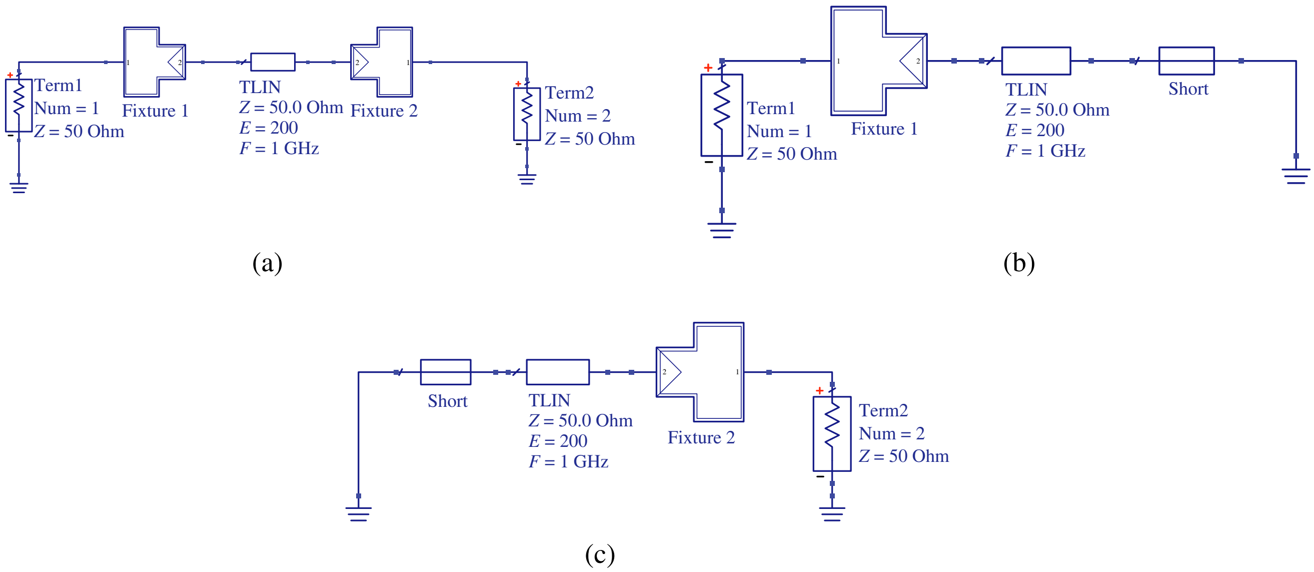

Figure 9. Schematics used to extract S-parameters of two different fixtures. (a) Schematic of the through standard comprised of two fixtures. (b) Schematic of short circuit for fixture 1. (c) Schematic of short circuit for fixture 2.

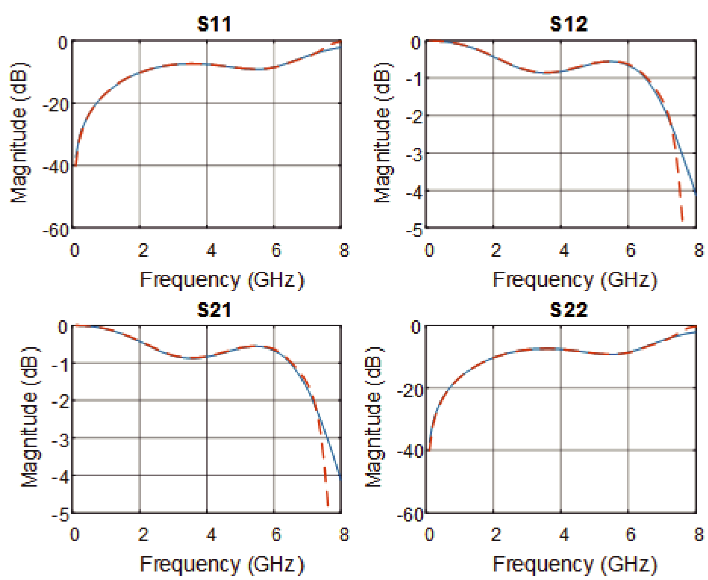

Figure 10. Comparison of fixture 1 characteristic (blue trace) with that extracted characteristic (red trace).

In order to remove the effect of $C1$ from the measurements, we can use a time-domain gate to choose a time domain response related to $C2$ (The time domain response that is related to the $C1$ is removed). Because $C1$ represents a masking error for the time-domain gated measurements, the $C1$ S-parameter needs to be extracted for compensating the masking error. The extracting method described above can be used to extract the S-parameters of $C1$.

The S-parameters of $C1$ can be used to remove the masking error in the time-domain gated measurements. As show in Fig. 7, the time-domain gated and compensated measurement coincide closely with the desired part of the DUT. It should be noted that the only compensates for the magnitude of masking error in this experiment and other measurements except the measurement data of the DUT are not required. The deviation at the band edge response is caused by the time domain gate [12].

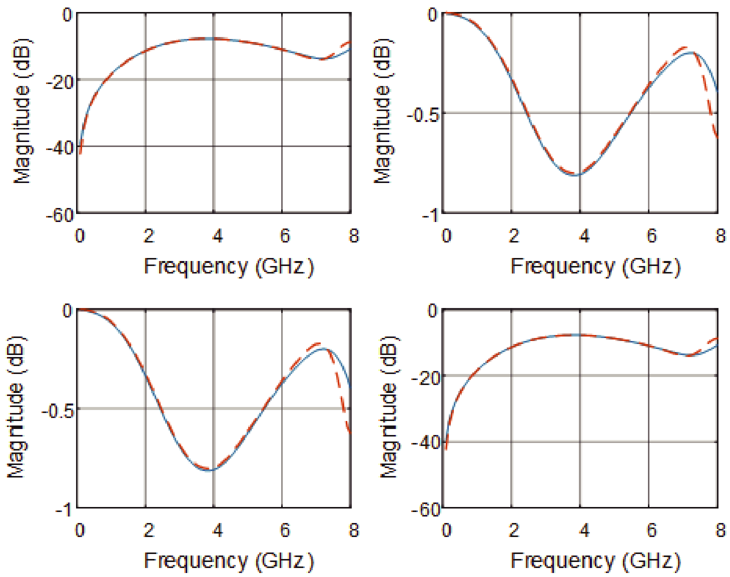

Figure 11. Comparison of fixture 2 characteristic (blue trace) with that extracted characteristic (red trace).

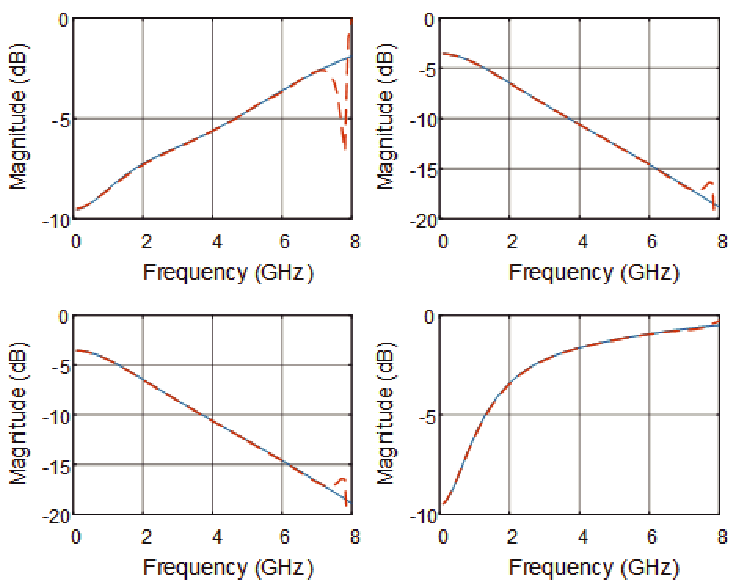

Figure 12. Comparison of original DUT characteristic (blue trace) with that de-embedding result by the method described in this paper (red trace).

3.2. De-Embedding of Two Different Fixtures

An experiment for de-embedding fixtures is introduced. The fixtures are lossless and reciprocal.

The composite measurement of the DUT and two fixtures combination can be measured from the schematic shown in Fig. 8. In order to obtain the characteristics of the DUT, the fixture S-parameters need to be obtained and the effects of the fixtures de-embedded.

A standard circuit is built as the schematics in Fig. 9 and the fixtures S-parameters can be extracted by the method described in this paper.

The S-parameters of the fixtures are shown in Fig. 10 and Fig. 11. The extracting S-parameters of the fixtures are consistent with the measurements of the fixtures.

The S-parameters of the DUT can be obtained by de-embedding the effects of the fixtures from the raw measurements. The result for the de-embedding fixtures is consistent with the measurements of the DUT. The deviation at the band edge is caused by the time domain gate.

This de-embedding experiment validates the extracting method introduced above.

4. CONCLUSION

An S-parameters extraction method using time-domain gates is introduced. Two simulation experiments are used to validate the method. This paper discusses how to compensate for masking error or extract the characteristics of fixtures, but the key point in this paper is to introduce a new method to extract the desired network S-parameters from the original measurements by time-domain gates according to the signal flow diagram.

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