

Time Domain Gating of Microwave Component Responses Using Analog Techniques

Abstract — This paper describes an analytical technique for Time Domain Gating of RF / microwave components. Vector fitted rational function approximations will be used to describe S-parameters in the time domain. Properties of the Laplace Transform will be taken advantage of in order to perform gating on both the time domain reflection and transmission responses. Following the development of the gating technique, theoretical and measured examples will be presented to show the applicability of the technique described. This novel approach allows for time gating of measured and synthesized data. Additionally, gated time and frequency response data can be retained and used as a design input for development of microwave assemblies.

Index Terms — S-parameters, Time Domain Reflectometry/Transmission, gating, vector fitting, macromodel, rational approximation.

I. INTRODUCTION

In the early days of microwave measurements, pieces of measurement equipment including power meters, oscilloscopes and wavemeters were used [1, 2]. In subsequent years, network analyzers were developed that displayed the frequency response of microwave components [3]. Major network analyzer manufacturers developed add-on modules to perform time based measurements done with oscilloscopes.

Engineers also use network analyzers to move the measurement reference planes to characterize solely the component or device under test (DUT). Analytical techniques have been developed to determine the component's frequency response via de-embedding. This method has been well described and characterized in terms of both the matrix operations required and the practical implementation of these techniques with network analyzer measurement equipment [4].

In some cases, the connection methods used do not permit one to perform de-embedding. In these cases, a technique called time domain gating can be used. Dunsmore, from KeySight Technologies, has described in detail the development, implementation and application of time domain gating techniques for measurement of typically passive, microwave devices [5]. A key reason for Dunsmore for developing these methods was implementation onto measurement equipment; this naturally led to use of digital signal processing techniques and discrete time methods to traverse between the time and frequency domains [6].

Another major development that has occurred is the advent of communication system simulations. It is necessary to include time domain RF / Microwave behavior in these simulations. Both continuous and discrete time methods are used for converting frequency domain data to the time domain. Discrete time methods are very similar to those used in time domain modules in network analyzers [7]. The continuous time method

allows one to take measured frequency domain data and fit an equivalent Laplace domain partial fraction expansion to this data [8]. In order to calculate these quantities one would use commercial software products such as MATLAB. Then, by use of either built-in or user defined functions, a user can do detailed analysis on these measured results including time domain reflectometry and transmission analysis.

In the next section, a mathematical method is described for gating both time domain transmission and reflection responses using an analog or continuous time technique. This method can be implemented as a function in software and both time and frequency gated responses can be calculated and plotted. Two examples are then presented. In the first, a theoretical case is used for verification of the method. A second case will use measured data to demonstrate the practical use of the method proposed.

II. FORMULATION FOR GATING VECTOR FITTED RESPONSES

It is assumed that for a given S-parameter element, it will have both a time and complex frequency domain representation [9] and can be described as:

$$F(s) = \int_0^{\infty} f(t)e^{-st} dt. \quad (1)$$

The integration span given in (1) is modified so that the Laplace Transform can be determined over a finite time span, say between t_1 and t_2 , and is given by:

$$F^{gate}(s) = \int_{t_1}^{t_2} f(t)e^{-st} dt = \int_{t_1}^{\infty} f(t)u(t - t_1)e^{-st} dt - \int_{t_2}^{\infty} f(t)u(t - t_2)e^{-st} dt \quad (2)$$

where $u(t)$ is the Heaviside step function [9]. Each of the terms on the right hand side of (2) can be re-written as:

$$\begin{aligned} \int_{t_n}^{\infty} f(t)u(t - t_n)e^{-st} dt \\ = \int_0^{\infty} f(t' + t_n)u(t')e^{-s(t'+t_n)} dt', \quad (3) \end{aligned}$$

where n is an integer. The result from (3) leads to:

$$F^{gate}(s) = \int_0^{\infty} f(t' + t_n)u(t')e^{-s(t'+t_n)} dt'. \quad (4)$$

A general result for describing time gating has been given and to make it readily useable, the given formulation needs to correspond with the general vector fitting format [8]. The general Laplace Transform representation of this is given by:

$$F(s) \approx \sum_{i=1}^I \left(\frac{c_i}{(s-a_i)} + d \right) e^{-t_d s} \quad (5)$$

where a_i is a vector fitted pole, c_i is the residue calculated for pole a_i , d is the extrapolated behavior at infinite frequency and t_d is the electrical time delay through the microwave component [8]. To obtain a useable result, the expression in (4) needs to be evaluated with a specific class of function. The general function that is used is:

$$f(t) = c_i e^{a_i t}. \quad (6)$$

When substitution of the right hand side of (6) into (4) occurs, the following result is obtained:

$$F^{gate}(s) = \int_0^\infty c_i e^{a_i(t'+t_n)} u(t') e^{-s(t'+t_n)} dt'. \quad (7)$$

When the integrand on the right hand side of (7) is evaluated a result that is useable in (5) is realized, as demonstrated:

$$F^{gate}(s) = \frac{c_i}{(s-a_i)} e^{a_i t_n} e^{-(t_d+t_n)s}. \quad (8)$$

The result in (8) represents a single term of the summation series given in (5).

The only thing left to determine is the appropriate value for the quantity, d [8]. For transmission, secondary reflections are gated out [3] and the value of d is set to zero, i.e. $d = 0$. When determining this same constant term for reflection responses, the Initial Value Theorem [9] can be applied and the value of d will simply be $d = f(t_n)$.

III. METHOD VALIDATION

A. Theoretical Validation Example

The theoretical example is a cascade of an ideal 3-section Bessel lowpass filter and a near ideal transmission line. In Table 1, the lowpass filter's component values as well as the transmission line parameters including length and distributed element parameters are listed. Using MathWorks' RF Toolbox add-on to MATLAB, analysis of the components and the component cascade is performed. Synthesized data is calculated over a frequency range of DC to 20 GHz.

Once the structures are cascaded, vector fitting of the cascaded S-parameters is carried out so as to convert the S-parameters into a time domain format [8]. For the element, S_{11} , a suitable fit is found with 55 poles and for element, S_{21} , a 57 pole fit is chosen. To determine the time domain representation of S_{11} , an ideal step function is applied to the vector fitted, S_{11} quantity. Response data is calculated to 10 nanoseconds with time steps of 20 femtoseconds.

Time gating is done to remove the effect of the lowpass filter and extract the transmission line reflection response with the end goal of matching the near ideal transmission line response. The reflection responses for the cascaded network, the transmission line and the gated network are shown in Fig. 1. Comparison of the transmission line and gated responses in Fig. 1 indicates that there is good agreement between the extracted and theoretical lobe levels. Frequency nulls are not in perfect alignment. However there appears to be an acceptable level of correspondence between the two responses giving confidence

that the proposed method is viable for gating measured RF / Microwave data.

For this theoretical case, time gating of the Time Domain Transmission (TDT) response is also performed to remove all of the tertiary reflections caused by the lowpass section [3]. In order to do this, the TDT response has a gate start time around 2.0 nanoseconds. In Fig. 2, both the original and gated TDT response plots are shown, where the y-axis is zoomed in upon to see fluctuations in the settling behavior of the network response. With the time gating applied, the secondary reflection is removed, thus, achieving the desired result of gating the TDT response.

B. Measurement Based Example

The measurement example has three RG58 coaxial cables connected together via a tee with the perpendicular piece remaining an open stub. The cables connected between the input and output connectors have a physical length of 0.9398m (37in) and the open stub is 0.3048m (12in). S-parameter measurements of the assembly are taken up to a frequency of 1 GHz. Time gating is done in order to extract the reflection response of one of the main line RG58 cables. A suitable fit for the measured S_{11} element is found with 28 poles. In order to match the transmission line frequency response, the network reflection response is gated between 38.35 and 48 nanoseconds. The network and gated time based reflection responses are shown in Fig. 3. In Fig. 4, the frequency domain reflection responses of the tee network, one of the transmission line sections and the time gated section are all plotted. Conventional figures of merit yield a worst case matching difference of 3 dB between the extracted and measured cable responses. It should be noted that the extracted response exhibit behavior that is consistent with theoretically based transmission line models. For instance, the frequency response nulls are fairly evenly spaced at integer multiples of 103.5 MHz. Looking at the frequency response peaks, all peaks are within 0.2 dB of each other over the frequency range.

IV. CONCLUSION

An analytical technique has been described for performing time gating on both reflection and transmission responses of RF / Microwave components. The analytical method was tested with a theoretical reference case and measured RF data. Results in each case gave confidence that this technique is a viable option for performing time gating operations on measured RF / Microwave data. The method provides engineers another way to carry out time gating on measured RF / Microwave data and does not depend on signal processing limitations such as windowing for example.

REFERENCES

- [1] Agilent Fundamentals of RF and Microwave Power Measurements (Part 1), Application Note 1449-1, Agilent Tech., Santa Rosa, CA., 2003, pp. 6-8.
- [2] C.G. Montgomery, "The Measurement of Wavelength," *Technique of Microwave Measurements*, volume 11 of *MIT Radiation Laboratory Series*. McGraw-Hill, New York, 1947, pp. 308 – 320.
- [3] D. Ballo, "Network Analyzer Basics", Hewlett Packard, Santa Rosa, CA., 1997 Back to Basics Seminar, April 1997.
- [4] Agilent De-embedding and Embedding S-Parameter Networks Using a Vector Network Analyzer, Application Note 1364-1, Agilent Tech., Santa Rosa, CA., 2004, pp. 4 -8.
- [5] J.P. Dunsmore, *Handbook of Microwave Component Measurement: with Advanced VNA Techniques*, West Sussex, United Kingdom: Wiley, 2012.
- [6] J.P. Dunsmore, "Gating Effects in Time Domain Transforms," presented at the ARFTG Conference, Portland, OR., 2008.
- [7] J.P. Dunsmore, "The Time-Domain Response of Coupled-Resonator Filters with Applications to Tuning," Ph. D. dissertation, School of Electronics and Electrical Engineering, Univ. Leeds, Leeds, England, 2004.
- [8] B. Gustavsen, and A. Semelyn, "Rational Approximation of Frequency Domain Responses by Vector Fitting," *IEEE Trans. on Power Delivery*, vol. 14, pp. 1052-1060, July 1999.
- [9] S.L. Campbell, *An Introduction to Differential Equations and Their Applications*, Belmont, CA: Wadsworth, 1990, pp. 209-256.

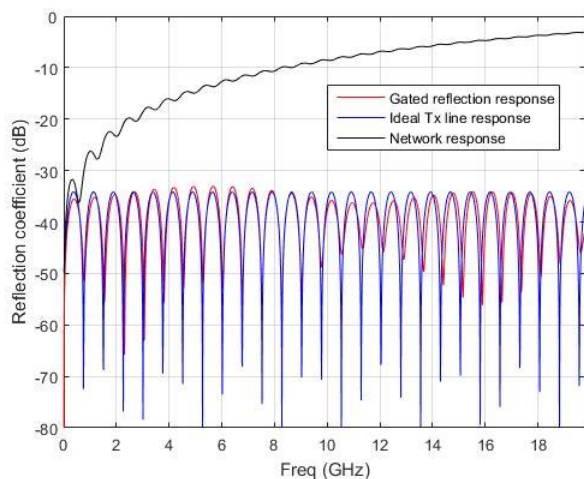


Fig. 1. Input reflection response for Filter – Tx line cascade, Tx line and the Gated Reflection response.

TABLE I
LOWPASS FILTER COMPONENT VALUES
TRANSMISSION LINE PARAMETERS

Lowpass Filter		Transmission Line	
Component	Parameter Value	Component	Parameter Value
L1 (nH)	0.877	R (ohm/m)	0.1
C2 (pF)	0.154	L (nH/m)	266.67
L3 (nH)	0.134	G (Siemens/m)	0.001
		C (pF/m)	102.56
		Length (m)	0.127

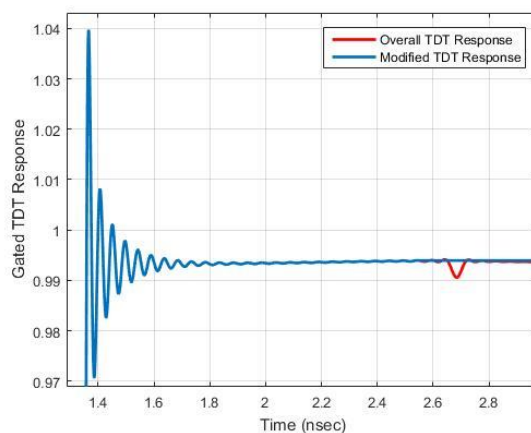


Fig. 2. Comparison between the TDT Response of the lowpass filter / transmission line cascade and the Gated Response with reflections removed.

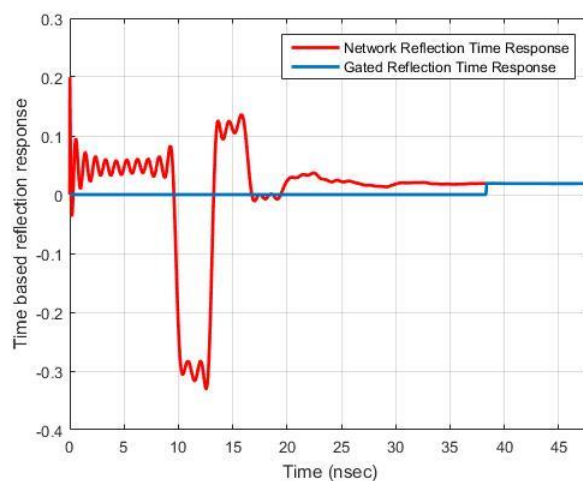


Fig. 3. Measured and gated reflection responses for the RG58 cable assembly.

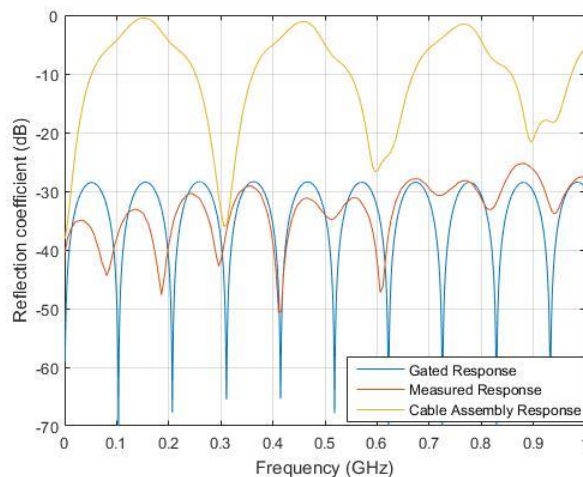


Fig. 4. Measured reflection responses for the tee network, and an individual cable plotted along with the extracted cable response.