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Real-Valued Discrete-Time Impulse Response Representation of Bandpass S-parameters

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Abstract— Accurate and efficient time-domain simulation techniques for broadband microwave networks at system level are highly desirable in modern computer-aided-design (CAD) tools, because of advantages in terms of high simulation speed and the reduced requirement for full circuit-level details of the simulated networks. A method for accurate time-domain representation of bandpass S-parameters is proposed in this paper, in order to produce fast time-domain steady-state responses of broadband high-frequency linear, time-invariant systems. A real-valued discrete-time impulse response (DTIR) representation is used in the proposed method. As a result, the processes of down-conversion and up-conversion of input signals and system bandpass transfer functions normally required in bandpass analysis, can be effectively avoided. For example, the method can be used in the design of distortion cancellation circuits in full-duplex communication systems.

Keywords—bandpass S-parameter; computer-aided-design; discrete-time impulse response; full duplex; the Hilbert transformation relationship; time-domain representation

I. INTRODUCTION

Engineers are discovering more and more practical applications for high-frequency electromagnetic signals, for instance: Wi-Fi mainly uses the 2.4 GHz and 5 GHz radio band; WirelessHD operates at the 60 GHz band; imaging technology utilizes THz radiation, etc. In order to satisfy the simulation requirements of high-frequency and broadband operation for these application scenarios, increased demands are placed on CAD techniques in order to speedily and accurately describe the complex characteristics of the microwave components and systems in these new environments.

In general, microscopic models for microwave devices, such as physical models, equivalent-circuit models, and nonlinear differential equation models, require a knowledge of the detailed physics of the devices in order to produce their comprehensive descriptions on a fundamental component level. Conversely, macroscopic models, such as system-level models or behavioral models, can effectively avoid resorting to the fundamental physics of devices, because macroscopic models are based on the external responses of the devices rather than their internal configurations. System-level macroscopic models utilize relatively simple mathematical formulations involving a small number of coefficients to approximate a possibly quite large circuit, resulting in a significantly reduced computation time during simulations.

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On the other hand, time-domain simulations of linear time-invariant microwave systems are often highly desirable for broadband operation. Time-domain analysis of microwave networks is the most basic simulation approach, since in reality all components naturally work in the time-domain. However, nonlinear active devices and linear passive devices are not traditionally simulated in the same domain, although these two types of components are often distributed and mixed in practical microwave systems. Active devices are usually described in the time-domain in order to accurately present the time-variant nonlinearities of the active devices. The linear passive subnetworks are generally described in the frequency-domain, because the time-domain simulation of the distributed passive components, such as microstrip lines with frequency-dependent propagation constant and characteristic impedance, can encounter difficulty in achieving acceptable accuracy [1]. In contrast, frequency-domain parameters, such as S-parameters, can describe the passive components simply and precisely. Therefore, the time-domain representation of baseband and bandpass S-parameters is an important issue for describing linear time-invariant microwave networks over a broad bandwidth. Moreover, when using an impulse response format for the representation, a time-domain simulation can be accomplished by a convolution between the network's time-domain representation and input signals.

The time-domain representation of *baseband* S-parameters using real-valued finite impulse responses or using real-valued infinite impulse responses has been studied previously [2-5]. In this paper, a real-valued discrete-time impulse response (DTIR) representation method is proposed to describe *bandpass* S-parameters in the time-domain. By using real-valued DTIR representations, the processes of down-conversion and up-conversion of input signals and bandpass S-parameters used in conventional methods [6-7], are effectively avoided. As a result, the digital and analog circuit implementations can be simplified. For example, when the bandpass S-parameters of a circulator as used in a full duplex radio block are provided, an analog cancellation can be implemented using programmable attenuators and time delays only [8]. This is because phase shift components are not needed for the implementation of real-valued DTIR representations of bandpass transfer functions.

In the following, the proposed method is set out in Section II. Afterwards, in Section III, experiments are provided for frequency-domain and time-domain verification of the proposed method. In addition, comparisons among analytical

simulation results, Keysight ADS transient simulation results and the results derived from the proposed method are presented to prove the accuracy and robustness of the method presented here. Finally, some conclusions are drawn in Section IV.

II. THE PROPOSED METHOD FOR TIME-DOMAIN REPRESENTATION OF BANDPASS S-PARAMETERS

A. Extrapolation of Bandpass S-parameters

If a baseband S-parameter can be converted into a Hermitian function, while at the same time the Hermitian function is a continuous function after periodic extension, the baseband frequency-domain S-parameter can be represented in the time-domain by a real-valued causal impulse response through using the inverse discrete Fourier transform (IDFT) on the Hermitian function.

However, a bandpass frequency-domain S-parameter $S_{r,i}(f)$ cannot normally be converted into a Hermitian function, because of the absence of samples at low frequencies. Therefore, it is reasonable to consider extrapolating the bandpass S-parameter data from the measured minimum frequency f_{min} to 0 Hz. At the same time, in order to guarantee the extrapolated function to be continuous after being converted into Hermitian function and after periodic extension, a second extrapolation of the bandpass S-parameter can be carried out for the frequency band from the measured maximum frequency f_{max} to the Nyquist frequency $f_{Nyquist}$, where $f_{Nyquist} = 2f_{max}$ [4].

A demonstration of the real part of the extrapolated bandpass S-parameter $\bar{S}_{r,i}(f)$ is shown in Fig. 1. The real part of $\bar{S}_{r,i}(f)$ is denoted as $\bar{S}_r(f)$ and the imaginary part of $\bar{S}_{r,i}(f)$ is denoted as $\bar{S}_i(f)$. The real-valued causal DTIR representation of $\bar{S}_{r,i}(f)$ is denoted as $\bar{H}(t)$.

Fig. 1. A demonstration of the real part of the extrapolated S-parameter in the frequency band from 0 Hz to $f_{Nyquist}$.

Since the S-parameters are measured for linear time-invariant networks, when $\bar{S}_{r,i}(f)$ function is identical to the original $S_{r,i}(f)$ in the band of interest ($[f_{min}, f_{max}]$), $\bar{H}(t)$ can accurately describe the original $S_{r,i}(f)$ in the time-domain. Moreover, accurate time-domain steady-state responses of the simulated network in the band of interest can be produced using $\bar{H}(t)$.

In order to guarantee the causality of $\bar{H}(t)$, a Hilbert transform relationship is applied to $\bar{S}_r(f)$ in the proposed method. As a result, when an extrapolated real-part function $\bar{S}_r(f)$ has been obtained, the imaginary-part $\bar{S}_i(f)$ can be found directly using the Hilbert transform [10]. Therefore, it is not necessary to design extrapolation functions for both $\bar{S}_r(f)$ and $\bar{S}_i(f)$. Of course, the $\bar{S}_i(f)$ function must be constrained to equal the original $S_i(f)$ in the band of interest.

B. Extrapolation Function Determination

The $\bar{S}_r(f)$ is designed to be a piecewise-continuous function using polynomial functions as basis functions. In order to provide a smooth $\bar{S}_{r,i}(f)$ function for conversion to Hermitian form, a constant value is assigned above f_x . The proposed $\bar{S}_r(f)$ function can be expressed as follows:

$$\begin{cases} a0 + a1(f - f_x)^2 + a2(f - f_x)^4 & 0 \leq f < f_{min} \\ S_r(f) & f_{min} \leq f \leq f_{max} \\ a3 + a4(f - f_x)^2 + a5(f - f_x)^4 & f_{max} < f \leq f_x \\ a3 & f_x < f \leq f_{Nyquist} \end{cases} \quad (1)$$

where $a0, a1, a2, a3, a4, a5$ are unknown coefficients; f_x is an unknown frequency. The initial value of f_x is between f_{max} and $f_{Nyquist}$.

Under the continuity requirement of using the IDFT for causal time-domain responses, the Hermitian function of $\bar{S}_{r,i}(f)$ should be continuous after periodic extension. Two restrictions are proposed as follows:

$$a0 + a1(f_{min} - f_x)^2 + a2(f_{min} - f_x)^4 = S_r(f_{min}), \quad (2)$$

$$a3 + a4(f_{max} - f_x)^2 + a5(f_{max} - f_x)^4 = S_r(f_{max}). \quad (3)$$

After implementing the Hilbert transformation on $\bar{S}_r(f)$, $\bar{S}_i(f)$ can be obtained.

The calculated $\bar{S}_i(f)$ is restricted by (4) to solve the unknowns $a0, a1, a2, a3, a4, a5$ and f_x in an iterative way.

$$S_i(f) = \bar{S}_i(f) \quad f_{min} \leq f \leq f_{max}. \quad (4)$$

Another noteworthy restriction is that the magnitude of $\bar{S}_{r,i}(f)$ should not be larger than one, as expressed in (5):

$$|\bar{S}_{r,i}(f)| \leq 1. \quad (5)$$

This is because the magnitude of S-parameters measured from passive networks cannot be greater than unity. Equation (1) can converge successfully after a small number of iterations.

C. Causal Real-Valued Uniform DTIR Representation

The Hermitian function of $\bar{S}_{r,i}(f)$ has even symmetry in the real part and odd symmetry in the imaginary part. The design in subsection B can guarantee the Hermitian function of $\bar{S}_{r,i}(f)$ will be continuous after periodic extension. At the same time, as a result of using the Hilbert transform relationship between $\bar{S}_r(f)$ and $\bar{S}_i(f)$, the time-domain response of $\bar{S}_{r,i}(f)$ should be a real-valued and causal DTIR after the IDFT is applied to $\bar{S}_{r,i}(f)$.

When calculating the steady-state time-domain responses of the simulated networks in the band of interest, only the non-

zero-valued impulse response weights located at the beginning of the causal time-domain record are of practical interest. The number of the non-zero-valued impulse response samples produced by the proposed method is typically less than 100.

III. EXPERIMENTS AND VERIFICATIONS

A number of linear time-invariant microwave networks have been successfully tested to verify the proposed method. An example of one such experiment is given in the following.

The schematic of the arbitrary linear time-invariant microwave network used in this experiment is shown in Fig. 2.

Fig. 2. Schematic of an arbitrary linear time-invariant microwave test network.

The S21 parameter of the network is measured from 5 GHz to 15 GHz. Fig. 3 shows the real part of the extrapolation function designed by using the proposed method and the real part of the originally measured S21 data. The unknowns $a_0, a_1, a_2, a_3, a_4, a_5$ and f_x are respectively calculated as $-0.0465, 4.4712 \times 10^{-4}, -8.974 \times 10^{-7}, -0.0217, 0.0116, -3.3475 \times 10^{-4}, 20.621$.

Fig. 3. Real part of the extrapolated function and the real part of the original S21 data.

Fig. 4 shows the calculated $\bar{S}_i(f)$ in the originally measured band and the imaginary part of the measured scattering parameter, which is $S_i(f)$. From Fig. 4 we can see that the imaginary part calculated by using the proposed method can fit the original $S_i(f)$ very accurately.

Fig. 5 provides the whole picture of the real and imaginary parts of the Hermitian function of the extrapolated $\bar{S}_{r,i}(f)$. It is seen in Fig. 5 that the continuous Hermitian function of $\bar{S}_{r,i}(f)$ exhibits even symmetry in the real part and odd symmetry in the imaginary part. For this reason, the time-domain response of this Hermitian function will be real-valued and causal.

Fig. 4. Imaginary part of the extrapolated function in the originally measured band and the imaginary part of original S21 data.

Fig. 5. The real and imaginary parts of the Hermitian function of $\bar{S}_{r,i}(f)$

Fig. 6. The real-valued causal DTIR representation of $\bar{S}_{r,i}(f)$ in a uniform time-step format.

The real-valued causal DTIR representation of $\bar{S}_{r,i}(f)$ is shown in Fig. 6. This DTIR representation is in a uniform time-

step format. However, if the real-valued DTIR representation is in a non-uniform format, the number of non-zero valued impulse responses at the beginning of the causal time-domain representation can be greatly reduced [2]. This real-valued causal DTIR representation not only describes the Hermitian function in the Fig. 5, but also accurately describes the original S21 over the measured frequency band 5 GHz - 15 GHz.

By investigating the output response of the network under input excitations, time-domain verifications of the proposed method can be carried out. As an example, a two-tone signal is used: $\sin(2\pi f_1 t - 3\pi/4)$ and $\sin(2\pi f_2 t - \pi/4)$, where $f_1 = 6.25$ GHz and $f_2 = 12.5$ GHz. The proposed method is only effective when the input signal frequencies lie in the measured frequency band.

The comparisons of the time-domain output responses of the studied network simulated by analytical methods, the proposed method and the Keysight ADS transient simulator are shown in following figures.

Fig. 7. The time-domain verification of the proposed method by time-domain steady-state responses comparisons.

Fig. 8. The comparison of transient responses of the simulated network between the proposed method and the ADS transient simulator.

Fig. 7 shows the time-domain steady-state responses of the network. It is shown that the proposed method perfectly matches the results simulated by the analytical method and the ADS transient simulator.

Fig. 8 shows that the full time-domain transient response of the network simulated by the three methods. The purely transient part of the response decays to zero at around 3.5 nsec. The proposed method only utilizes bandpass S-parameters to produce the time-domain representation, and therefore the low- and high-frequency data required for determining the exact transient response is absent. Hence, as shown in Fig. 8, it is not surprising that the early transient response produced by the proposed method is different from the exact result. However, in most practical situations, the steady-state response of networks is of greater interest for analysis purposes.

IV. CONCLUSION

In this paper, a method based on real-valued causal time-domain representations of bandpass S-parameters is proposed. Extrapolation functions for the given bandpass S-parameters are designed in order to guarantee the causality and real-valued characteristic of the time-domain representations. Several frequency-domain and time-domain verifications are presented to show the high accuracy of the proposed method. Moreover, the proposed method shows robustness and efficiency for both time-domain representation and simulation.

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