FAST TRANSIENT SIMULATIONS FROM S-PARAMETERS WITH IMPROVED REFERENCE IMPEDANCE

By

MOHD RIDZUAN BIN KHAIRULZAMAN

A Dissertation submitted for partial fulfillment of the requirements for the degree of Master of Microelectronic Engineering

JANUARY 2015

ACKNOWLEDGEMENTS

First of all, I would like to thank Allah for giving me an opportunity to complete this thesis within the time frame. I would also like to express my appreciation and gratitude to my supervisor, Dr. Patrick Goh Kuan Lye, for the patience, guidance and knowledge shared during difficult times.

In addition, I would like to thank the Universiti Sains Malaysia for supporting this research with the Short-Term Grant 304/PELECT/60312048. Lastly, I would like to thank my parents and friends for the motivation, supports and the faith they had in me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES AND ILLUSTRATIONS

LIST OF ABBREVIATIONS AND NOMENCLATURE

Abbreviation	Meaning
C	Capacitance
CAD	Computer Aided Design
EDA	Electronic Design Automation
FFT	Fast Fourier Transform
G	Conductance
IFFT	Inverse Fast Fourier Transform
L	Inductance
MOR	Model Order Reduction
PWL	Piecewise Linear
R	Resistance
RF	Radio Frequency
S-Parameter	Scattering Parameter
SPICE	Simulation Program with Integrated Circuits Emphasis

ABSTRACT

As a design becomes more sophisticated, analyzing it becomes more complicated, and supporting high data speeds and high operating frequencies becomes more challenging. Conventional transient simulation can be a troublesome and a computationally expensive procedure, as the process takes a long time to complete. Hence, a fast transient simulation is utilized based on scattering parameter (S-parameter) convolution. This alternative approach to the S-parameter offers stability, efficiency and robust computation. In this research, the S-parameter frequency domain convolution was presented, which was later converted to impulse response or time domain data using the inverse Fast Fourier Transform (IFFT) algorithm for the fast transient simulation of multiport interconnect network or typically addressed as a black box model. Subsequently, the S-parameter convolution can be further improved by optimizing the reference system of the model. An improvement by 64% and 29.5% of IFFT point usage numbers with Black Box 1 and Black Box 2. These results respectively were obtained based on optimal reference impedance assigned in S-parameter synthesis on black box models, thus speeding up the convolution program, compared to the nominal reference impedance of 50Ω used to perform the fast transient simulation. Besides, the optimization routine implemented on the design has smoothed the magnitude of the S_{11} waveform and there is no significant effect observed on the time domain response.

ABSTRAK

Oleh sebab reka bentuk menjadi semakin canggih, menganalisisnya menjadi lebih rumit, dan menyokong kelajuan data yang tinggi dan kekerapan operasi yang tinggi menjadi lebih mencabar. Simulasi transien konvensional boleh menjadi sukar dan prosedur pengiraan yang mahal, kerana proses mengambil masa yang lama untuk disiapkan. Oleh itu, simulasi transien yang cepat digunakan berdasarkan konvolusi *scattering parameter* (S-parameter). Pendekatan alternatif kepada S-parameter menawarkan kestabilan, kecekapan dan pengiraan yang teguh. Dalam kajian ini, konvolusi domain frekuensi S-parameter telah dibentangkan, yang kemudiannya ditukar kepada data impuls respons atau domain masa menggunakan algoritma *inverse Fast Fourier Transform* (IFFT) untuk simulasi transien yang pantas bagi sambungan rangkaian berbilang port atau biasanya ditujukan sebagai model kotak hitam. Selepas itu, konvolusi S-parameter boleh dipertingkatkan lagi dengan mengoptimumkan sistem rujukan model. Peningkatan sebanyak 64% dan 29.5% penggunaan nombor titik IFFT dengan Black Box 1 dan Black Box 2. Keputusan ini masing-masing telah diperolehi berdasarkan rujukan impedans optimum ysng diberikan dalam sintesis S-parameter pada model kotak hitam, dengan itu mempercepatkan program konvolusi, berbanding dengan 50Ω impedans rujukan nominal yang digunakan bagi melakukan simulasi transien yang pantas. Selain itu, rutin pengoptimuman yang dilaksanakan pada reka bentuk gelombang magnitud S_{11}

yang telah dilicinkan dan tiada kesan yang ketara diperhatikan pada respons domain masa.

CHAPTER 1

INTRODUCTION

1.1 Project Background

Traditionally, in signal integrity simulation and modeling technique, the passive component of the interconnect or the transmission lines is treated by utilizing lumped networks, which consist of resistance (R), inductance (L), conductance (G), and capacitance (C) components per unit length. It is typically formulated using the simulation program with integrated circuits emphasis (SPICE) for transient simulation, essentially to be causal and passive at a slow data rate, thus promising accuracy and robust data. However, as the data rate increases, the interconnect becomes more complex and the nature of the interconnect becomes more dispersive as the result [1]. These factors contribute to the transition of implementing the scattering parameter analysis to simulate the passive distributed component for the signal integrity transient simulation.

Scattering parameter, also known as the S-parameter, is the scattering matrix or S-matrix element widely used in the electrical networks of radio frequency (RF) and microwave frequency for signal channel modeling. It characterizes the frequency domain behavior of electrical signals transmitted inside the multiport network, or interconnect, often treated as a black box or a complex model. The model extraction, based on the S-parameter in touchstones format, offered flexibility, accuracy and prompted sharing among vendors, as it is IP-protected. In order for it to be incorporate into the SPICE simulation, the tabulated S-parameter data must be converted to the lumped element model data for the transient simulation using the convolution technique. As the design becomes increasingly complex at high frequency or speed, maintaining model extractions that are stable, causal and passive, is difficult. Besides, it is very CPU computationally expensive to perform the convolution especially on complex models [1].

Macro modeling approaches are developed and embedded into the passive distributed network to alleviate the expense operation of the processor in handling complex models, whereby the tabulated scattering parameter data generated by the network analyzer of the full-wave 3D field simulator were sampled and computed over a frequency range [2]. The sampled S-parameter data are converted to the impulse responses, which are later convolved using inverse Fast Fourier Transform

(IFFT) in simulating the distributed network for transient convolution [3]. Passivity and causality enforcements need to be taken care of in order to obtain an accurate, robust, and reliable impulse response model used for the transient analysis. There is a list of literature that discusses the method in mitigating the time-consuming convolution driven by the transient simulation, as in [4] to [9]. More recently, [9] proposed the fast convolution method, which promised robustness, accuracy, as well as a fast and easy implementation with no curve fitting and passivity enforcement needed.

In [10], research has been evaluated to improve the fast transient simulation by optimizing the reference impedance, which, in turn, can reduce the amount of time it takes to run the simulation and the minimum number of IFFT sampled points needed to simulate the convolution technique. It take into consideration the reference impedance at a low frequency, to match the actual characteristic impedance of interconnect or the complex model, as closely as possible. However, due to the dispersive nature of the complex interconnect model at high frequencies, the passive distributed model is not comparable to structure wavelength, thus the delay effect in the time domain analysis can be adhered to in order to describe the behavior of the model [11].

The nominal reference impedance, Z_o, of 50Ω is used by default to the accessibility of the measuring instruments available on the market. Theoretically, the maximum power transmitted occurred when the characteristic impedance of the interconnect model is matched with the termination impedance. In [12] to [14], studies have been carried out on defining the characteristic impedance for the interconnect model based on the S-parameter analysis. In this work, fast transient convolution analysis is demonstrated, based on formulae in [14] with the iterative algorithm to determine the characteristic impedance of the complex model based on the S-parameter, considering 20% of 10GHz frequency range is covered in the black box model.

1.2 Problem statement

Simulation and modeling techniques on multiport, or the interconnect network, become challenging as the design becomes more complex at high frequencies. Under these circumstances, conventional transient simulation can be a troublesome and a computationally expensive procedure. Thus, fast transient simulation is presented based on S-parameter convolution. S-parameter convolution of frequency domain data takes place by implementing the IFFT to obtain the impulse response or the time domain data, which are later used in performing fast transient simulation of the complex or the black box model. An alternative approach using the scattering parameter offered a more stable and robust computation, with a more efficient algorithm. Besides, in this work the S-parameter convolution is further improved by optimizing the model's reference system. Analysis computes targeting minimal IFFT sampled points needed with respect to the optimal reference impedance, defined based on tabulated S-parameter data measured using the black box model operating at a high frequency.

1.3 Objectives

The objectives of this research are listed below:

i. To obtain the propagation delay of the black box models using the V-t waveform at the internal impedance of 50Ω.

ii. To determine consistent and stable optimal reference impedance, $\widehat{Z_o}$, of black box models within a range of frequency, based on the obtained propagation delay.

iii. To perform fast transient convolution, based on the optimal reference impedance, $\widehat{Z_o}$, obtained by targeting the smallest number of IFFT points needed.

1.4 Research Methodology

The work will focus on the important parameters that need to be considered, and on the methods used, as stated below:

i. Perform V-t analysis on the assigned black box port using the internal impedance of 50Ω and 1V of voltage supply at 0.5ns rise time.

ii. Measure the propagation delay of the interconnect model within 20% to 80% of the nominal voltage range.

iii. The propagation delay is the function of the interconnect routing and characteristics. It is later used to translate the physical length of the transmission line.

iv. Plot the S-parameter waveform for the frequency response analysis.

v. Choose the peak of magnitude S11 (within 20% of 10GHz frequency range).

vi. To mark the frequency later used to obtain the optimal reference impedance, $\widehat{Z_o}$.

vii. Determine the $\widehat{Z_o}$ based on the information and the algorithm, using the formula with the free space impedance assumption.

viii. Perform fast transient convolution based on the $\widehat{Z_o}$ obtained, compared to the conventional reference impedance, Z_o, of 50Ω for the optimal IFFT sampled point needed.

1.5 Thesis Organization

In this thesis, literature review and works recently done by researchers will be addressed in performing the fast transient convolution simulation. The characteristic impedance of the complex or the black box model based on S-parameters analysis will be discussed in Chapter 2.

Chapter 3 will cover the methodology designed for the analysis carried out for the fast transient simulation on the high-speed complex model based macro modeling approach. S-parameter frequency domain characteristics and behavioral synthesis will be demonstrated to define the optimal reference impedance.

The proposed method, based on the graphical illustration of computed and measured data, and the results, are discussed in detail in Chapter 4.

Finally, Chapter 5 summarizes and concludes the work presented. Recommendation and future work will be proposed for further assessment.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this section, previous studies done by researchers are discussed, with a special focus on studies where fast transient simulation, based on the S-parameter at optimal reference impedance, was successfully obtained. Literature review covers the macro model approach toward the high-speed complex model taking S-parameter synthesis into consideration. Besides, the characteristic impedance calculation exhibit on multiport, or interconnect networks are brought up in order to define optimal reference impedance for the smallest number of IFFT points needed to perform the fast transient analysis.

2.2 Convolution

Convolution is a mathematical expression of the output signal measured by convolving the input signal with the impulse response. It can be expressed in terms of the time domain response or the frequency domain response. Convolution uses frequency domain Z or Y parameters, which are later converted to the time domain response using the inverse Fast Fourier Transform. IFFT is commonly used because it offers efficiency and robustness. However, on lossy interconnect networks, this approach is not stable, as the impulse response duration exceeds the network transit time, resulting in severe aliasing errors [15]. Hence, an alternative approach that promises robust computation and an efficient algorithm, using the scattering parameter (S-parameter), was later used. The S-parameter can be obtained using actual measurement such as network analyzer of field electromagnetic solver tools.

2.2.1 Scattering Parameter

The scattering parameter, or the S-parameter, is used to characterize microwave circuits, illustrated by the power at the conservative terminal excitation of the design modeled. It is used to represent the incident and the reflective wave of the high-frequency response of the black box model, typically controlled by the 50Ω measurement system [16] to [17]. Conventionally, the interconnection design, represented by electrical parameters, namely, resistance, inductance, capacitance and conductance, is presently used to represent numerical/digital data in radio frequency (RF) or microwave communication [18]. However, due to operating frequency and integration density, the effects of signal integrity and quality are not well preserved, thus a different characterization technique of a complex model needs to be taken into account. Notwithstanding the various technical solutions proposed, the S-parameter extraction [19] to [22] has become the common method, especially for complex circuitry, as it is a fast and accurate method in the frequency domain.

With respect to fast transient simulation proposed in [8] and [9], the S-parameter is used to replace the state of the art method using curve fitting of rational approximation. The impulse response of the S-parameter is modeled as a discrete impulse, and controlled by the IFFT for the time domain convolution.

2.2.2 Fourier Transform Approach

There are two types of operation used in the Fourier Transform family known as the Fast Fourier Transform (FFT) and the inverse Fast Fourier Transform (IFFT), typically applied in convolution procedures. It applies the theory that multiplication in the frequency domain corresponds to convolution in the time domain [23]. Figure

2.1 illustrates the uses of the FFT and the IFFT in a convolution program based on the S-parameter.

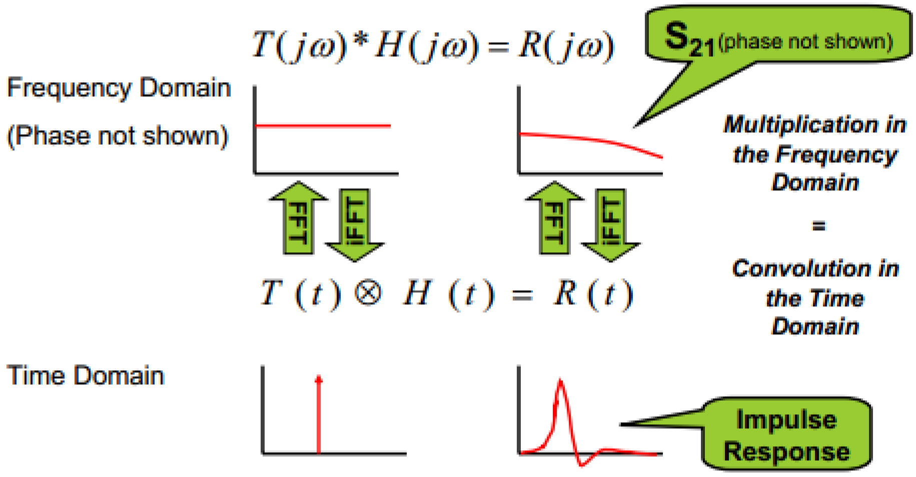

Figure 2.1: The S-parameter at the frequency domain and the time domain responses [23]

In setting up the fast transient simulation based on the S-parameter, the IFFT algorithm was proposed to obtain the time domain or the impulse response. Basically, the frequency domain S-parameter data are converted to the time domain response, which are then used in the transient simulation.

2.3 Transient Simulation of Macromodel

The multiport, or the interconnect design, becomes more complex as the frequency and the integration level increase, thus requiring proper care in order to achieve high operational performance and reliability. Numerous transient simulation techniques associated with the interconnect network have been proposed, as discussed in [24] to [28]. In [28], the conversion of the frequency characteristics to time domain description or the impulse response, was done using the inverse Fast Fourier Transform (IFFT) or the numerical inverse Laplace transform, also known as Green's algorithm. The signal behavior with respect to time can be determined by convolving the impulse response at the terminal excitation. However, it is time consuming to perform direct convolution, thus it is a computationally expensive process. Consequently, it indeed introduces signal noise, such as ringing and aliasing error in the response data due to band limiting caused by taking numerous frequency samples [3], [29].

A common approach, known as the time domain macro model, is developed to alleviate high computational time and the composition of the time and the frequency domain analysis, based on generated recursive convolution algorithm for the multiport or the complex model in transient simulation and modeling [30] to [31]. The impulse response is expressed as the sum of exponentials in time, or the sum of multiple zero-state ramp responses occurring at every point of different slopes up to the current time, assuming that the input voltage is piecewise linear (PWL) [32]. It is a rational function approximation of the S-domain, whereby the S-domain represented the Laplace transform variable. This technique was derived using the Padé approximation or the moment matching technique for efficient circuit simulation [31] to [35].

Other than that, the curve fitting technique, has been evaluated to approximate the black box model for poles and residue. It is known as the model order reduction (MOR) technique, based on the recursive convolution algorithm [36] to [38]. In [39] and [40], a parametric reduced orders were developed to further optimize the parametric dependency on the design cycle and process, allowing variation on the parameter with no repetition of the reduction step of a large interconnect network. This technique offers efficiency and accurate model derivation, which is compatible with standard computer aided design (CAD) and an EDA program based on the tabulated frequency response computed by a full-wave electromagnetic simulator [41].

A simulation involving the complex interconnect needs to be evaluated at a wideband frequency, whereby the macro model techniques employed for the high-speed complex or the black box model replaces the high model order of the measurement data by the fitting model approach [42]. This interactive approximation technique is applied on sampled frequency domain tabulated data [43]. More recently, the vector fitting approach have been adopted which yields accuracy, bandwidth, and computational complexity in approximating the transfer function of the distributed passive network. In fact, enhancements have been developed as shown in [6], [44] to [48].

The state-of-the-art multiport or interconnect networks exhibit high data rates, computational low power, and require passivity and causality enforcement in the event of deteriorating design signal quality. Thus, the distributed passive model, better known as the black box model, must be robust. In the meantime, the simulation and modeling techniques applied must be able to provide accurate, reliable and efficient data. Recently published papers [8] and [9], cited in this work, deal with passive multiport networks for fast transient simulations, using the S-parameter, which offers robustness and ease of implementation. This technique requires no curve fitting, delay extraction, or passivity synthesis, thus providing a faster algorithm, based on the delta convolution function.

2.3.1 Fast Transient Simulation

A multiport or an interconnect black box for the simulation and modeling techniques can be represented as illustrated in Figure 2.2. The black box model, with n-ports, is connected to the individual source and the termination.

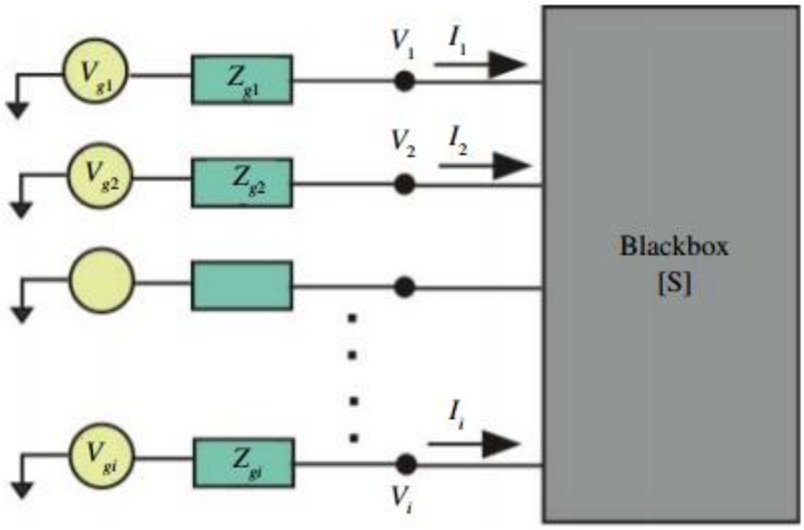

Figure 2.2: Multiport network of the black box model for a conservative source and termination [8]

The S-parameter can be represented at frequency and time domains as formulated by equations (1) and (2), respectively. Subsequently, the S-parameter convolution can be reformulated as shown in (3).

$$s_d(q) = \sum_{k=1}^{L} c_k e^{j2\pi qk} \tag{1}$$

$$s_d(u) = \sum_{k=1}^{L} c_k \delta(u-k) \tag{2}$$

$$h_d(p) = \sum_{k=1}^{L} c_k \delta(u-k) \, * \, a_d(p) = \sum_{k=1}^{L} c_k a_d(p-k) \tag{3}$$

s_d denotes the discrete scattering parameter of frequency domain data, q and time domain data, u. c_k parameter is impulse train of L or order of the approximation, determined using IFFT of frequency domain transfer function.

Meanwhile, an excitation function of $a_d(p)$ are convolved with the discrete scattering parameter as shown in equation (3).

In performing the fast transient simulation based on the S-parameter, the causality enforcement requirement has to be fulfilled. Thus, the Hilbert Transform algorithm has to be satisfied, as indicated by equation (4) [8].

$$HT(f_k) = \hat{f}_k = \begin{cases} \frac{2}{\pi} \sum_{n\ odd} \frac{f_n}{k-n}, & k\ is\ even \\ \frac{2}{\pi} \sum_{n\ even} \frac{f_n}{k-n}, & k\ is\ odd \end{cases} \tag{4}$$

$\hat{f}_k$ represents the discrete variable of the Hilbert transform at superposition of even and odd relation for frequency domain data. Brief formulation can be obtained in [8]. Based on the relationship derived, the black box model of the S-parameter was modeled using a commercial tool and assessed for the delta function convolution using the IFFT algorithm, and later performed a fast transient simulation.

2.4 Characteristics Impedance

It is a recently formulated belief, as discussed in [10], that optimizing the reference impedance of the S-parameter can speed up the convolution program, resulting in minimal use of IFFT sampled points. The optimal reference impedance was determined by considering the impedance measured at a low frequency of the S-parameter, which is close to the actual characteristic impedance of the interconnect model. The idea is that the magnitude will always be zero for S_{11} and one for S_{12} if characteristic impedance is applied in the reference system of the S-parameter for the ideal interconnect network. Thus, the impulse response of S_{12} is just a single pulse or delay occurring in the model whereas S_{11} will always at a zero impulse response.

The characteristics impedance is used to represent the electrical behavior of the interconnect network. Over the decades, numerous studies have been done on defining the interconnect model characteristic impedance for simulation and modeling techniques [49] to [53]. The common approach used to determine the characteristic impedance of multiport networks or passive distributed components is by using the S-parameter.

Multiport or interconnect models are designed based on the function of the frequency and the position of the characteristic impedance over the geometry of the network. As the frequency increases, the wavelength of the design is shorter than the interconnect physical length. Thus the electrical behavior of interconnect model becomes more complex, which, in turn, lowers the accuracy and the reliability of the data measured [54]. The S-parameter is characterized as being extendable up to a certain frequency, to illustrate the behavior of the design. However, it was limited up to 3GHz for the impedance calculation accuracy of the passive component [55].

Maximum power delivery to the load occurred when the load impedance equaled the characteristic impedance of the design. This fact allows the design to circumvent the reflection and the distortion that degrade the signal performance. Thus, a proper technique is needed to approximate the characteristic impedance of the black box model for data accuracy and reliability. In this work, paper [14] will be used as a guide to help configure the characteristic impedance for the black box model. This impedance is later used as reference for improving the convolution analysis.

As the frequency increases, the design become more complex, thus proper approximation in defining the characteristics impedance needs to be taken into account. In this work, the optimal reference impedance is defined based on the S_{11} formulation, as shown in (5) [14].

$$\hat{\hat{z}}_o^{\,2} + \frac{2i_{s11}}{tan\theta(r_{s11}-1)}\hat{\hat{z}}_o + \frac{1+r_{s11}}{1-r_{s11}} = 0 \qquad (5)$$

$\widehat{\hat{z}_o}$ is obtained by normalizing the characteristic impedance, $\widehat{Z_o}$ to the terminating impedance at output/ input port. The normalized real and imaginary magnitude of S_{11} are defined by r_{s11}, and i_{s11} respectively. θ represents the electrical length of the interconnect model, is the product of the physical length and the phase constant of the model. The estimation used to define the electrical lengths of black box models is discussed briefly in Chapter 3. There would be two possible value obtained based on the formulae, only one that is correct will be selected. The $\widehat{Z_o}$ is obtained by multiplying the $\widehat{\hat{z}_o}$ with nominal reference impedance, Z_o, of 50Ω.

Overall, fast transient simulation based on S-parameter convolution was presented in this work, combining the proposed methods discussed in [8] and [10]. An IFFT algorithm is applied for the convolution program on the multiport interconnect network, also known as the black box model. Further optimization routine was demonstrated to improve and accelerate the S-parameter convolution by properly choosing the reference impedance assigned to the system. To do so, an iterative algorithm is proposed to calculate the characteristic impedance, considering 20% of the 10GHz frequency range of the interconnect network modeled to establish accurate data reporting, considering the worst case return loss, the S_{11} condition. Table 2.1 shows the qualitative summary between this work and [10].

Table 2.1: Qualitative summary

Items	Previous method in [10]	Proposed method
Optimizing reference impedance at	Low frequency	High frequency (within 20% frequency range)
Interconnect model	Complex with unknown properties	
Transient simulation execution	One time (for $\widehat{Z_o}$ only)	Two times (for both Z_o and $\widehat{Z_o}$)
Propagation delay	-	Measured within 20% to 80% voltage reference of 50Ω transient response to estimate the physical length.
Physical length	-	Estimated by using propagation delay per unit length assumption (165ps/inch).
Determine characteristic impedance	By selecting the frequency which close to 0Hz.	By applying the equation (5), then multiply it with Z_o.
Method applied	Algorithm only	Combination of the formulae and the algorithm.

2.5 Summary

The background study of the macro model approach to high-speed complex models taking into consideration of the S-parameter synthesis and the determination of the optimal reference impedance of the interconnect network, based on the S-parameter, has been covered. This section also reviewed related works done by other researchers.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this section, the optimization of the reference system to speed up the S-parameter convolution is demonstrated in the process of performing fast transient simulation, based on the S-parameter. There were three (3) black box passive multiport interconnect network macromodels computed for the simulation analysis.

3.2 Fast Transient Simulation Based on S-parameter Convolution

Convolution analysis is a mathematical operation wherein the output, $y(p)$, is obtained by convolving the input, $x(p)$, and the impulse response, $h(p)$, indicated by the asterisk (*) symbol. This approach can be performed in the frequency domain or the time domain transfer function, and is typically used to determine the behavior of distributed element. The convolution of the input signal and the impulse response in the time domain is equivalent to multiplication in the frequency domain. Convolution via the frequency domain, which is later converted to the time domain response to obtain the voltages or the current of the interconnect networks using the inverse Fast Fourier Transform, IFFT, will be utilized as the algorithm, since it is an efficient and robust computation procedure.

In this work, the frequency domain scattering parameter (the S-parameter) transfer function on three sets of black box macromodels are assessed before being converted to the time domain S-parameters for post processing. The S-parameters represent the interconnect network characteristics over a wide range of frequencies that include all the high-order phenomena like dispersion, skin effects and so on. Typically, the S-parameter data of interconnect networks are described in terms of their magnitude and their signal phase over a frequency range. It is computed by exciting the wave travelling signal and the reference impedance of 50Ω terminated on the port of the model. The data are then converted into the real and the imaginary components of the frequency response.

The S-parameter approach to the convolution program offered robustness, due to the short lived nature of impulse responses [51]. The inverse Fast Fourier Transform is used to convert the frequency domain response of the S-parameter data to the time domain or the impulse response. The output signal of the transient response, results from convolving the input signal with the impulse response obtained from the IFFT applied. The IFFT impulse response computed can be a one-sided spectrum or a two-sided spectrum, indicated by the pulse of either a positive or a negative magnitude, or both. It can be indicated based on real and imaginary components of the S-parameter information of the complex input data. A one-sided spectrum occurs when the imaginary part is equal to zero, whereas a two-sided spectrum results if the imaginary part is nonzero.

Subsequently, the fast transient simulation based on the S-parameter, is performed. A pulse response of 1V voltage source at 0.5ns rise and fall time with delay and pulse widths of 5ns and 4ns, respectively, were excited on the model of a 50Ω reference impedance.

3.3 Optimization Routine on the Reference Impedance of the S-parameter

Fast S-parameter convolution can be accelerated by carefully selecting the termination impedance assigned for the reference system of the black box macromodels. The common reference impedance assigned for simulation and modeling is 50Ω by default. Basically, the reference impedance can be varied to obtain optimal S-parameter performance. Considering the match impedance concept, the characteristic impedance of the black box is defined and used to further improve the convolution program. Also, it is proven that in an ideal interconnect network, the magnitude of S_{11} will always be zero and the magnitude of S_{12} will always be equal to one if the characteristic impedance is applied to the reference system of the S-parameter. Thus, the impulse response of S_{12} is just a single pulse or delay occurring in the model whereas S_{11} will always be at the zero impulse response.

3.3.1 Characteristic Impedance Formulation

As the frequency increases, the design becomes increasingly complex. Thus the importance of proper approximation in defining the characteristics impedance, $\widehat{Z_o}$, needs to be taken into account. In this work, the characteristic impedance of the interconnect network can be determined using equation (5), considering the return loss of the S-parameter, S_{11}, information [14]. There would be two possible values obtained, based on the formulae, only one of which is correct. This solution will be used and the other is to be disregarded. In this work, the neglected value is the negative value, which will obtain invalid characteristic impedance. Meanwhile, the positive value will obtain the correct solution.