Chapter 1

Introduction

The Transmission Line Matrix method (TLM) is a well established time domain technique for the simulation of the transient behavior of an electromagnetic problem of the most general type. These problems may involve nonlinear, inhomogeneous, anisotropic and time dependent material properties. The TLM was first introduced by *P.B. Johns* and his coworkers in 1970's [1].

The method is based on the discretization of the Huygen's principle of wave propagation in space and time. A three dimensional space is simulated by a mesh of orthogonal transmission lines interconnected at the nodes. The mesh is excited at some points by impulsive sources. The impulses are incident on the nodes where they are partially reflected and partially transmitted according to the transmission line theory. The reflected and transmitted pulses then become incident on neighboring nodes where they are scattered again and so on. These consecutive scattering events are responsible for wave propagation according to Huygen's principle as demonstrated in [2], [3] and [4].

The development of three dimensional nodes has followed several stages. It started with the expanded node which was a direct combination of two-dimensional series and shunt nodes. However, this node in addition to being complicated, had the disadvantage of the fact that different field components and polarization are calculated at points that were physically separated [2,5]. Further development of three-dimensional nodes introduced an improved node that were able to overcome the difficulties associated with the expanded node which was the symmetrical condensed node (SCN) [6]. Other nodes were also introduced which proved to have superior characteristics in terms of computational efficiency and numerical dispersion, these are: a pair of hybrid symmetrical condensed node (HSCN) [7,8] and the symmetrical super condensed node (SSCN) [9,10].

Although the TLM method was originally derived in the time domain for the simulation of the transient behavior of electromagnetic problems, some work has been devoted to the development of a frequency domain TLM (FDTLM) capable of combining the flexibility of the conventional TLM with the computational efficiency of frequency domain methods.

One of these methods was developed by *Vahldieck* in 1992 [11] for the selective S-parameter computation of 3-D waveguide discontinuities. The idea of this technique was to excite the mesh with an impulse train of sinusoidal modulated amplitude simulating a sinusoidal excitation. Consequently, for a linear system, the transfer characteristic of the system at the frequency of the excitation is contained in the amplitude of the output sinusoidal wave. For adequate convergence to steady state, generally several periods at the source frequency had to be covered. The modeling of the medium parameters, scattering and connection in that FDTLM mesh is exactly the same as TDTLM. The approach had the advantage of saving the unnecessary processing of all the transients associated with an impulsive excitation. Also, the required information is directly calculated from the output magnitude rather than Fourier transform. The other important advantage was the ability to handle multimode structures as indicated in [11].

The second FDTLM method was introduced by *Johns* and *Christopoulos* in 1994 [12], [13]. The heart of this approach was the determination of a set of simultaneous equations involving the incident voltages at each node and the source or excitation nodes. The set of equations were then solved for the steady state incident voltages using the Jacobi method or the conjugate gradient method. In both approaches discussed, the simulation has to be repeated at every frequency point as in the case of most frequency domain methods, to compute the response over the frequency band of interest.

The two FDTLM approaches mentioned above are in fact different in their nature and abilities. The first one [11] was in fact a time domain TLM (TDTLM) dealing with a steady state analysis in the time domain. The method was claimed to reduce the computational time if the response is only required at distinct frequency points. The second approach [12,13] was a true FDTLM with a steady state analysis in the frequency domain.

In this work, a novel frequency domain TLM approach is introduced based on a steady state analysis in the frequency domain using transient techniques, and hence will be referred to as TFDTLM. In this approach, the link line impedances are derived in the frequency domain, as in [13], to satisfy all the medium parameters including frequency dependent parameters as well as electric and magnetic losses. The scattering matrix is derived in a similar way to any 3-D TLM node. The connection between two adjacent cells, expressed in the from of delay in the time domain, is expressed by multiplication with a propagation factor $e^{-\gamma l}$, where γ is the propagation constant in the medium. The steady state solution is obtained iteratively as in a TD TLM mesh.

To make the proposed TFDTLM approach computationally efficient as compared to the other frequency domain TLM approach [13], it was critical to maintain some relationship between the mesh response at one frequency point and any other frequency point. The goal was to be able to extract all the frequency domain information in a wide frequency range by performing only one simulation. To achieve this, the transitions between two adjacent cell expressed by ($e^{-\gamma l}$) have to be expressed in terms of the propagation factor of some reference medium chosen to be the medium with the least propagation delay. This was done with the aid of a digital filter approximation that can be implemented iteratively inside the TLM mesh. The filter can be thought of as some type of compensation equivalent to the stubs in a TDTLM, yet more accurate and more general.

The new TFDTLM has all the powerful capabilities of the second FDTLM [12,13], basically being able to model the electrical variation of the medium parameters without the need to add stubs in addition to being able to model frequency dispersive constitutive parameters directly and more accurately. The very special feature of the new approach is the fact that only one simulation can cover all the information in a wide frequency range without the need to redo the simulation at every frequency point. This means that all the superior features of the time domain and frequency domain TLM are combined in the new TFDTLM approach.

In this dissertation, Chapter 2 will review the time domain TLM. In Chapter 3, the transient frequency domain TLM (TFDTLM) will be introduced. The technique used to overcome the problem of inhomogeneous media, multiple propagation factors and frequency dependent reflection coefficients will be discussed. In chapter 4, the dispersion behavior of the SCN, the HSCN, and the SSCN will be analyzed. The dispersion characteristics of the TFDTLM will also be derived and compared to that of the HSCN and the SSCN. In chapter 5, the TFDTLM will be implemented in a three dimensional mesh. Some 3-D structures will be simulated and the ability of the TFDTLM to accurately model wave propagation in lossy inhomogeneous media will be demonstrated. Chapter 6 includes a summary and conclusions.