Localization of a Discharge in Transmission Line Networks using Time Reversal with TLM

Wolfgang J. R. Hoefer

Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, V8S 2N3, Canada
whoefer@ece.uvic.ca

Abstract **─** The location of an electrical discharge in a transmission line network is found from its recorded transient response by means of a time reversal simulation. The accuracy of the localization procedure depends on how closely the simulator models the wave properties of the network that must be linear, reciprocal, and virtually loss-free. TLM simulations are presented.

Index Terms **─** Electrical discharge, electromagnetic simulation, source reconstruction, time reversal, transmission line networks.

I. INTRODUCTION

Finding the location of an electrical discharge is an important issue in electromagnetic compatibility and interference (EMI/EMC) [1]. A discharge in a complex transmission line network produces a transient signal that propagates and scatters through the entire system. As time moves forward, the signal becomes increasingly distorted due to multiple reflections, scatterings, and multipath transmission, looking less and less like the original excitation waveform. Nevertheless, this time response contains, at any point in the network, sufficient information to recover the discharge location, provided that the network is linear and reciprocal, and has negligible losses. All we need is an accurate computational space-time model of the network, such as a Transmission Line Matrix (TLM) or a Finite Difference Time Domain (FDTD) model, to reconstruct this location from the output signal picked up and recorded at one or more points in the original network. This procedure is based on the computational reversal of time and amounts to injecting the time-reversed output signal back into the model, yielding the origin of the disturbance.

The use of time reversal as a method for solving inverse problems, such as finding an unknown source from its known emitted field, dates back to the late 1950s and has been applied extensively in optics, acoustics, seismology, and electromagnetics. For a list of references and a general introduction to time reversal, see the recent article on "Time Reversal in Electromagnetics" by the author [2]. Inverse problem solutions such as time reversal procedures, can be mathematically and computationally complex. However, a time domain electro-magnetic simulator is a powerful tool for solving such problems with ease, accuracy, and speed, as demonstrated by the example presented below. The essence of the computational time reversal procedure will be summarized in terms of a correlation performed by the simulator.

II. THE EXAMPLE SCENARIO

A. Topology of a transmission line network

Figure 1 shows an arbitrary transmission line network example used to demonstrate the localization procedure. It consists of several interconnected TEM transmission lines, two of them matched, and the rest short-circuited. We assume that an electric discharge occurs at time $t=0$ at the position *n*, and the network response is picked up at two probes (nodes) *m1* and *m2*. To facilitate the visualization of the electromagnetic events, the figure shows the 2D model of a real structure as it appears in the Editor window of the TLM simulator MEFiSTo-3D Pro. It is the top view of a network of parallel-plate transmission lines with magnetic side walls drawn in blue in the *xy*-plane (H-plane), while the electric field is normal to the page.

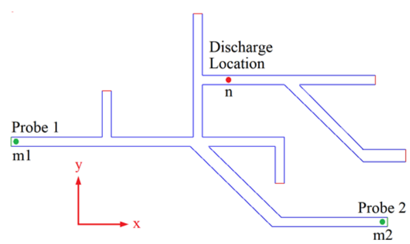

Fig. 1. Transmission line network consisting of TEM waveguides (top view).

B. Electromagnetic response to a discharge

The first step is to obtain the electromagnetic response of the network to a discharge at location *n*. In a real-world experiment, the response is physically recorded at *m1* and *m2*, and stored for further processing. However, in order to derive a general discrete Green's formulation of the time reversal procedure for the problem, we shall generate this response with the same

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space-time discrete TLM model that will be used later for the recovery of the source location. Note that the time variable is now discretized into steps of Δt and defined as $t=k\Delta t$, where k is the integer time index. We assume at first that the discharge at $t=0$ $(k=0)$ is modeled by a unit impulse or Kronecker Delta function $\delta(k,k')$, which has the value unity at time step $k=k'$. (We can later extend the solution by convolving the impulse response with a more realistic excitation waveform). The computed impulse response e_z at any output node m to a unit excitation $e_z(n,0)$ at input node n and at time $k'=0$ is:

$$e_z(m,n,k) = g(m,n,k). \tag{1}$$

This response to a unit impulse is a discrete Green's function, shown in Fig. 2 as recorded at locations *m1* and *m2* for the first *3 ns* (*K=424* time steps) following the excitation event.

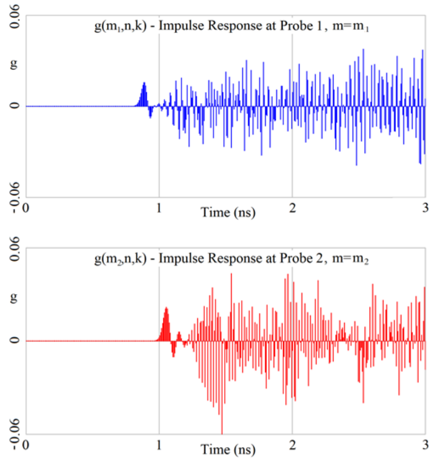

Fig. 2. The impulse responses *g(m,n,k)* at locations *m=m1* (top) and *m=m2* (bottom) are terms of the discrete Green's function of the network.

C. Time reversal of the impulse responses

The source location is now recovered by flipping the above impulse responses in time and re-injecting them back into the TLM model at the probes where they have been initially recorded. These responses are essentially finite sequences of K real numbers, where K is the total number of time steps. The inverse of a response *g(m,n,k)* is written as *g(m,n,K-k)*. When it is injected back into the model as a source signal for a second simulation, the TLM simulator effectively convolves it with its own impulse response *g(m,n,k)* by virtue of its reciprocity property [3]. We write this as:

$$A(n,k) = g(m,n,k) * g(m,n,K-k). \tag{2}$$

The symbol $*$ designates a numerical convolution. *A(n,k)* is defined in signal processing as the *autocorrelation* of *g(m,n,k)*. The signal computed at any location other than that of the original impulse excitation will be the *cross-correlation* of two different terms of the discrete Green's function, which will typically be an order of magnitude smaller than the auto correlation product. Hence, we only need to inspect the final field distribution computed by the TLM solver at $k=K$ and look for the location at which the field has a maximum value.

III. RESULTS OF THE TIME REVERSAL COMPUTATION

Figure 3 shows the distribution of the computed electric field e_z in the network at the end $(k=K)$ of the inverse TLM simulation. It is essentially a map of correlation products of terms of its discrete Green's function. All are cross-correlation products, except for the autocorrelation term that occurs at the original source location and clearly stands out, revealing the location of the discharge with mesh resolution. Note that one impulse response recorded at a single probe is already sufficient for reconstructing the source.

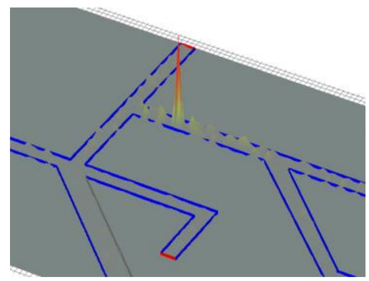

Fig. 3. The electric field distribution in the network at the end of the inverse simulation shows a clear maximum at the location of the original unit excitation. The impulsive excitation provides mesh resolution. (Mesh size $\Delta\ell=1mm$).

IV. DISCUSSION AND CONCLUSION

To achieve highly accurate results, it is essential to have a very good model of the transmission line network under investigation. In the above example this was guaranteed since we used the same TLM model to perform the forward and inverse simulation. However, in a practical surge localization problem the forward propagation occurs in a real structure, while the inverse source reconstruction is performed by simulation. Furthermore, the waveform produced by a real surge looks more like a double exponential pulse and has a narrower spectrum than the Kronecker Delta function, resulting in a reduction of spatial resolution.

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