Multiresolution Time Domain Modeling for Large Scale Wireless Communication Problems

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Abstract

The time-domain modeling of large scale wireless communication problems arising in wireless communication channel analysis and design studies is discussed in this paper. It is pointed out that the use of the conventional Finite Difference Time Domain method for the treatment of such problems typically results in long, computationally burdensome simulations that limit the utility of this technique to provide an efficient CAD-oriented tool for commercial and military applications. For this purpose, a multiresolution time-domain model is described along with techniques to improve the efficiency of the simulation.

I. Introduction

With the recent advances in mobile communications and their growing use in both consumer and military applications, the rigorous analysis of electromagnetic interference (EMI) between antennas mounted on neighboring platforms has become a topic of critical importance. In particular, the concurrent operation of transmitter systems in proximity with each other and their resultant parasitic interference, can potentially drive their power amplifier stages to saturation, causing the well-known effect of intermodulation. Furthermore, it was recently demonstrated that the incorporation of active element components and nonlinear circuits in the FDTD mesh can be easily accomplished by following a state equation based approach. However, if FDTD is a second-order accurate scheme and sensitive to numerical dispersion, a dense discretization of at most ten, but usually twenty five points per wavelength is necessary for the extraction of a convergent solution. Hence, the FDTD treatment of electrically large domains corresponding to systems of create multiple transceivers (even in VHFBased operation) yields a computationally intensive, memory and execution time consuming calculation.

Moreover, it was recently demonstrated that the incorporation of active element components and nonlinear circuits in the FDTD mesh can be easily accomplished by following a state equation based approach. However, if FDTD is a second-order accurate scheme and sensitive to numerical dispersion, a dense discretization of at most ten, but usually twenty five points per wavelength is necessary for the extraction of a convergent solution. Hence, the FDTD treatment of electrically large domains corresponding to systems of create multiple transceivers (even in VHFBased operation) yields a computationally intensive, memory and execution time consuming calculation.

For the alleviation of the computational burden involved in the FDTD simulations, this paper follows two directions of research. The first is the use of parallelization for the distributed update of the electromagnetic field values in the computational domain over multiple processors, while the second is the introduction of wavelets for the implementation of a space-time adaptive processing via the Multiresolution Time Domain (MRTD) technique [5], in the sense of [6]. The Haar wavelet basis is employed, for the reason that its update equations include only nearest neighbor interactions, in contrast with higher order basis functions, whose stencil extends over several cells. Thus, the Haar basis is considered as a promising candidate for the application of parallel computing to MRTD.

In the following, the aforementioned modeling approach is explained in greater detail and numerical results regarding typical problems that this work aims to address are provided.

II. The Three Dimensional Haar MRTD Scheme

The three dimensional Haar wavelet based MRTD scheme is formulated in this section. For this purpose, all electric and magnetic vector components are expanded in three dimensional Haar scaling and wavelet functions \( \psi_0 \), \( \psi_1 \), \( \psi_2 \) with \( r = 0, 1, \cdots, \nu \) being an index denoting the resolution of the wavelet tree (varying from \( \nu \rightarrow 0 \) to \( \nu \rightarrow \infty \)), and \( \psi_i \) being a count of the \( r \)-order wavelets within each cell. The mathematical definition of the Haar scaling and wavelet functions is given in [5]. It is noted that the introduction of one wavelet level (zero order) in \( \psi_0 \), \( \psi_1 \), \( \psi_2 \) is expected to bring about an improvement in resolution of a factor of two per direction (hence, eight in total) compared to a scaling only based scheme. However, for this to be true, a certain condition regarding the arrangement of electric and magnetic field nodes need to imposed, as discussed in [6]. Namely, as the offset of field and magnetic field nodes is half a cell in FDTD, an \( r \)-order Haar MRTD (of \( r \rightarrow 1 \) wavelet levels) this offset must be

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set equal to one cell by $2^{i-2}$. For example, the $E_y$ component of the electric field is expanded as:

$$E_y(x, y) = \sum_{n=1}^{\infty} b_n(x) \sum_{r, s} \left\{ a^{n}_{r, s, x} \left[ \psi (x) \phi (s) \phi (s) (x) \right] + a^{n}_{r, s, y} \left[ \psi (x) \phi (s) \phi (s) (x) \right] \right\}$$

$$+ \sum_{r, s} \left\{ a^{n}_{r, s, x} \left[ \psi (x) \phi (s) \phi (s) (x) \right] + a^{n}_{r, s, y} \left[ \psi (x) \phi (s) \phi (s) (x) \right] \right\}$$

$$+ \sum_{r, s, z} \left\{ a^{n}_{r, s, x} \left[ \psi (x) \phi (s) \phi (s) (x) \right] + a^{n}_{r, s, y} \left[ \psi (x) \phi (s) \phi (s) (x) \right] \right\}$$

where $r' = i + 1/2^{r+1}$, $r_{max}$ denotes the maximum wavelength order in $x$-direction and $b_n$ are the pulse functions defined in [3]. The rest of the EM field components are accordingly defined. The combination of scaling and wavelet terms yields equivalent grid points whose arrangement (under the condition followed here) in the equivalent Vee's cell of MRTD is shown in Fig. 1, where $r_0 = 2^{i-2}$, $\xi = x, y, z$ (refinement factor). Finally, a dispersion analysis of this scheme shows that its dispersion characteristics are given by the expression:

$$\left( \frac{1}{\omega} \Delta z \sin \frac{\omega \Delta z}{2} \right) = \left( \frac{1}{\Delta z} \sin \frac{\omega \Delta z}{2} \right)^2 + \left( \frac{1}{\Delta z} \sin \frac{\Delta z}{2} \right)^2$$

where $\Delta z_{cell} = \Delta z/(2^{i-2} - 1)$. Equations (2) shows that unlike previous formulations of Vee MRTD that lacked the theoretically expected resolution properties [7], the scheme that is presented here does demonstrate an accuracy consistent behavior. The rest of our derivation follows the method of Moments based technique that is set forth in [3].

III. COSTE INTERFERENCE PROBLEM MODELING

A. Geometry / Open-Boundary

The general form of coste interference scenarios considered in this work is shown in Fig. 2, which depicts two neighboring vehicles or transceivers. Cases of more vehicular transceivers or multiple antennas mounted on the same platform is also considered. For the simulation of the open boundaries of the domain, a non-reflective PML absorber [8] is employed, for both FDTD and MRTD simulations. In particular, MRTD mesh truncation via an FDTD UPML is attained by means of an FDTD/MRTD interface, thus providing a step transition from the one engine to the other with no need for interpolations or extrapolations in either space or time [9]. The condition for the stable/deepeness matching of the two schemes, as given by Equation (2), is that the FDTD cell sizes be equal to the MRTD effective cell sizes. In our simulations, a separation of one to two wavelengths between the vehicles and a ten-cell absorber of non-reflective coefficient $\epsilon_{ref}(-16)$ has been sufficient for the extraction of accurate results.

B. Active Element

The assessment of the effect of coste interference on the operation of the transceiver front-end electronic equipment and especially input stage amplifiers is also of interest here. For this purpose, the extended FDTD method of [2] has been utilized. According to the method, circuit state equations (the circuit being the load in the antenna input port) are coupled with a Thévenin/Norton equivalent of the FDTD cell (derived by Maxwell's curl equations) in order to represent the circuit-wave interaction. This technique has been successfully incorporated in MRTD simulations [10], due to its versatility, circuit theory based character.

C. Parallelization

The parallel FDTD algorithm currently uses a static regular block based partitioning strategy in which each processor is assigned one block of the domain to work on. The computational workload is non-uniform across the domain with little or no computation performed for cells within a vehicle and additional computations for cells within the absorber regions. The partitioning strategy uses relative computational weights for each type of cell to adjust the subdomain boundaries and compensate for this imbalance. The MPI library is used for communication between processes owning neighboring cells.
IV. NUMERICAL RESULTS

The vehicle model that is used in our simulations is shown in Fig. 3. The vehicle trunk is considered as a perfect electric conductor, an assumption that is valid in the VHF band. The vehicle antenna is modeled as a monopole mounted on the rear part of the platform. Two case studies are presented here, both including two neighboring vehicular transceivers in hybrid operation (one is in transmit and the other in receive mode). This operation is simulated by using a transparent, 0.6 GHz Gaussian excitation at the gap of the first antenna. For the derivation of the following results, the FDTD method is employed in both a serial and parallel fashion, with Yee's cell dimensions being equal to 5 cm by 5 cm by 5 cm. The receiving antenna is terminated at a parallel RLC block with $R = 1 \, \Omega$, $L = 1 \, \mu F$, $C = 10 \, \mu F$, and is modeled by means of the state equation approach of [2]. It is noted that the antennas are $\alpha$-directed and considered as one cell thick and one meter long. Local sub-gridding techniques can be readily employed for the modeling of thinner monopoles. Finally, the time step is equal to 92 ps. For the execution of parallel runs, the HPN6 Blue Horizon single-processor Power3 based clustered SMP system is used. The system has 1152 processors, 512GB memory which are arranged as 144 SMP nodes each with 8 375MHz (HP Power3 processors and 4GB memory shared among them. Timing measurements correspond to 100 time-step runs, each being executed 5 times. Both average and minimum times are shown.

The first geometry under study is depicted in Fig. 4 and yields a relatively large working volume of 70 by 274 by 200 cells terminated into 10 UPML cells at each open boundary. Input current waveforms for the two antennas (derived by means of Ampere's law) are shown in Fig. 5. Even the apparent weak coupling between the two antennas can adversely affect the receive operation of the second and its sensitivity to signals coming from remote transmitters, when the spectral contents of the interfering signal is within the bandwidth of the input stage filter of the receiver [1]. For the validation of the active element modeling, the input impedance of the receiver is computed, by Fourier transforming the time-domain input voltage and current data of 8192 time steps. The resulting patterns of the parallel RLC combination is thus derived and compared successfully to its theoretical value (Fig. 6). Parallelizing the code, speed-ups of more than 90 were obtained on 128 processors (Fig. 7). Timing measurements for the same case are given in Fig. 8.

A second case study is shown in Fig. 9. Again, antenna 1 is considered as a transmitter, while antenna 2 is loaded by a parallel 3LC block, being in receive mode. The input current waveform at antenna 1 is almost identical to the one of the previous case (only differing at some low amplitude retro-reflections). Input current and voltage waveforms for antenna 2 are given in Fig. 10. Furthermore, Fig. 11 includes three snapshots of $E_z$ at time steps 400, 800, 1200 sampled at a $z-$plane that includes the transmitting antenna, clearly showing the metal tracks of the vehicles and the free space propagation of the excitation pulse that is emitted from the transmitter and eventually covers the whole space, illuminating the second vehicle. Finally, for this case, speedup of more than 85 was obtained on 128 processors (Fig. 12).

V. CONCLUSIONS

A research effort to rigorously model co-locate interference problems by time domain methods such as FDTD and MRTD, combined with parallelization strategies was described in this paper. Preliminary numerical results, based on the FDTD technique were derived as a basis for the physical understanding of the problem, that is fundamental for the fine-tuning of the adaptive wave used technique that we propose. The compatibility of our approach with SPICE type circuit simulators allows for the development of an integrated analysis tool for circuit and EMI phenomena pertinent to transceiver system performance under EMI conditions.

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Fig. 7. Parallel speedup curve for the geometry of Fig. 4.

Fig. 8. Execution time with respect to processors for the geometry of Fig. 4.

Fig. 9. Computational domain for the second coarse mesh refinement scenario (p2 - p3).

Fig. 10. Input voltage and current of scenario 2 of Fig. 9.

Fig. 11. Bz field pattern sampled at the 2-x plane containing vertices 1 in the geometry of Fig. 9.

Fig. 12. Parallel speedup curve for the geometry of Fig. 9.