

# Integration of FDTD EM Analysis and Transient Circuit Simulation of RF Systems

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**Abstract**—A combined transient simulation of a 300 MHz input, 20 MHz output RF radio transceiver system was performed using an industry standard FDTD simulator integrated with an open source state-variable based multi-physics simulator. The two simulators were interfaced at every time step and several nonlinear iterations were performed at each step in order to ensure simulation convergence of the system which contains strong nonlinearities and a wide range of signal strengths at different points in the system.

**Index Terms**—FDTD, transient simulation, radio, transceivers, CAD, dynamic range.

## I. INTRODUCTION

With the proliferation of sophisticated antenna and transceiver designs, the traditional separation between antennas and circuits has become blurred. Many antenna designs now contain integrated circuitry as well as other circuitry that includes active and passive devices with strongly nonlinear and time-varying characteristics. The design of such systems requires accurate modeling of both electromagnetic and electronic effects. In such scenarios, an electromagnetic simulation needs to include the effects of the complex interactions from voltages and currents present in the electrical portion of the system to properly account for their impact on the electromagnetic fields, thereby enabling fully physical modeling of device interactions with time-varying electromagnetic fields. Including these effects is essential when the environment consists of several closely-spaced antennas with the existence of multiple propagation paths, for example, radios in a densely crowded urban environment, impacted by co-site interference with some of the interference being relatively large. This is a particular problem when transmit and receive channels occupy the same frequency band as is the case with ad-hoc radios such as WiFi and military radios. Response signatures are impacted by the RF front-end components and subsystems including frequency-shaping by the antenna, the frequency selectivity of filters and in-band group delay variations and the radio's nonlinear components. Such an environment cannot be modeled using a linear frequency-domain characterization and requires the transient modeling of the nonlinearity of the communication devices contained therein.

High dynamic range is essential to model communication devices in the time domain. In the context of communication

scenarios, the dynamic range consideration concerns the difference between the minimum discernable signal and the largest undistorted signal within a specified communication band. The minimum detectable signal in simulation is often established by numerical noise of the algorithm. If the simulation is linear, the noise is spread more or less uniformly and only the in-band noise will affect dynamic range. However, in nonlinear circuit simulation, numerical noise in any part of the spectrum affects the dynamic range meaning very high levels of dynamic range are required. The dynamic range in the modeled electromagnetic environment can be quite low, but within the circuit that range can exceed 140 dB.

The Finite-Difference Time Domain (FDTD) method [1] is a well-developed and versatile method for directly solving Maxwell's equations in the time domain. A number of attempts have been made to couple FDTD electromagnetic solvers with circuit simulators and can be broadly divided into two approaches: In approach 1, as proposed in [2] for two dimensions, linear and nonlinear circuit element contributions can be inserted into Maxwell's equations by adding a lumped electric current density term thereby extending the FDTD formulation. This idea, for instance, has been extended to three dimensions to perform electromagnetic modeling of chip interconnects [3], for the modeling of digital signal propagation paths [4] and active antenna analysis [5]. This approach has also been used to interface a commercial electromagnetic and semiconductor device simulator as described in [6]. Approach 2, as briefly described in [7] is to directly interface the FDTD electromagnetic fields with the voltages and currents of linear and nonlinear models of electronic circuit components. This second approach makes use of the inherent advantages of circuit simulators which may not be applicable to three-dimensional FDTD solvers. The latter prefer to use single-precision arithmetic to save on memory at the expense of dynamic range. This approach has been used, for instance, in the analysis of packaged microwave circuits [8] and in analyzing the performance of multi-antenna systems on vehicles [9].

This paper presents the co-simulation, using the second approach mentioned above, of a strongly nonlinear bilateral radio transceiver system using XFDTD<sup>®</sup>, an FDTD simulator

developed by Remcom, Inc.<sup>1</sup>, and a multi-physics simulator, *fREEDA*<sup>TM2</sup>, developed at North Carolina State University. Compared to the work presented in [8], the FDTD simulator is a commercial industry-standard program and the circuit simulator is an object-oriented, state-variable based high-dynamic range simulator, [10], [11]. Although the electronic simulator used in [9] is also state-variable based and uses the second approach to interface the FDTD and electronic simulations, the interface element used is a linear source element and based on the architecture of that electronic simulator, it will perform only one iteration per time step. In order to solve problems with strong nonlinearities, such as the radio transceiver considered in this work, obtaining numerical convergence in general necessitates that the interface element perform several nonlinear iterations per time step. The work presented here satisfies this criteria and the simulation performed demonstrates the ability to model the high-fidelity time domain response of a radio transceiver circuit with both strongly nonlinear and dynamic characteristics.

## II. INTERFACE DESCRIPTION

XFDTD is a full wave electromagnetic solver employing the FDTD method in a memory and computationally efficient way. Complicated Computer-Aided Design (CAD) objects with thousands of parts may be imported into XFDTD using the internal graphical editor. RF designers can import electromechanical CAD files, improve the design using XFDTD and export the revised CAD file to reduce design time. Applications include microwave, RF, antennas, scattering, biological EM problems, packaging and electromagnetic behavior of specialized materials. XFDTD offers capabilities such as a Fast Meshing Algorithm, mesh preview before calculation and a wide variety of complex electric and magnetic materials. The time-domain solver supports true Message-Passing Interface (MPI) capability to enable calculations to be performed on computer clusters and also supports XStream<sup>®</sup> hardware to enable calculations using the Graphics processing Units (GPU) in high-speed video cards.

*fREEDA*<sup>TM</sup> is an open-source state-variable based multi-physics simulator that uses compact models [10]. The benefit of compact modeling is that properties of an object, such as a transistor, are captured as a collection of algebraic or differential equations which allows circuits using ubiquitous components that are created at considerable effort to be reused easily for any circuit. In general, a system in *fREEDA*<sup>TM</sup> is split into its linear and nonlinear components and the error function at the interface of these two parts is minimized. In other words, the linear and nonlinear parts of a system are balanced. The simulator contains a large catalog of linear and nonlinear elements, which include physically-accurate models of semiconductor devices as well as more generic behavioral models. It also supports several types of analysis routines in the time and frequency domains. In particular, it supports a

high-dynamic range transient analysis [11] which is essential to solving problems related to circuit and field interactions.

In order to interface the two simulators, a single state-variable nonlinear element was developed in *fREEDA*<sup>TM</sup>, hereby designated as the Interface Element (IE). As is well known, the conventional FDTD algorithm divides the solution space into so-called Yee cells and the assumption is that *fREEDA*<sup>TM</sup> interfaces with the XFDTD program at the face of a single Yee cell. An example Yee cell is shown in Fig. 1. In this figure, the H-fields are directed along the edges of the cube while the E-fields are obtained at the center of each face.

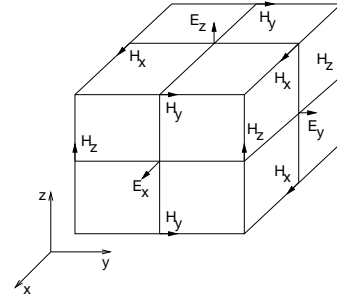


Fig. 1. A sample Yee cell.

The IE obtains the values of the current from XFDTD which is calculated by integrating the H-field along the edges of the cube face.

$$\mathbf{I}_{\text{interface}} = \oint_{\Gamma} \mathbf{H}(t) \cdot d\Gamma. \quad (1)$$

The conventional error function described in [10] is now modified to include this current contribution,  $\mathbf{I}_{\text{interface}}$ , provided by the nonlinear IE and becomes

$$\mathbf{G}\mathbf{u}_n + \mathbf{C}\mathbf{u}'_n = \mathbf{s}_{f,n} + \mathbf{T}^T[\mathbf{i}_{\text{NL}}(\mathbf{x}_n) + \mathbf{I}_{\text{interface}}(\mathbf{x}_n)] \quad (2)$$

where matrices  $\mathbf{G}$  and  $\mathbf{C}$  represent the linear passive and dynamic circuit components respectively,  $\mathbf{u}$  is the vector of linear terminal voltages,  $\mathbf{s}_f$  is the vector containing the source elements,  $\mathbf{T}$  is the circuit incidence matrix,  $\mathbf{x}$  is the state-variable vector,  $\mathbf{i}_{\text{NL}}$  is the vector of currents obtained from the nonlinear elements and subscript  $n$  represents time step. There is also a capacitive component present that is related to the dimensions of the Yee cell and it is included in the IE, but for sake of brevity, will not be shown in these equations. The time marching integration for  $\mathbf{u}'_n$  can be approximated by

$$\mathbf{u}'_n = a\mathbf{u}_n + \mathbf{b}_{n-1} \quad (3)$$

where  $\mathbf{b}_{n-1}$  is a vector of the same dimension as  $\mathbf{u}_n$ . Replacing  $\mathbf{u}'_n$  in (2) we get

$$\mathbf{G}\mathbf{u}_n + \mathbf{C}[a\mathbf{u}_n + \mathbf{b}_{n-1}] = \mathbf{s}_{f,n} + \mathbf{T}^T\mathbf{i}_{\text{NL}}(\mathbf{x}_n) + \mathbf{T}^T\mathbf{I}_{\text{interface}}(\mathbf{x}_n). \quad (4)$$

Solving for  $\mathbf{u}_n$ ,

<sup>1</sup>www.remcom.com

<sup>2</sup>www.freeda.org

$$\mathbf{u}_n = [\mathbf{G} + a\mathbf{C}]^{-1}[\mathbf{s}_{f,n} - \mathbf{C}\mathbf{b}_{n-1}] + [\mathbf{G} + a\mathbf{C}]^{-1}\mathbf{T}^T[\mathbf{i}_{\text{NL}}(\mathbf{x}_n) + \mathbf{I}_{\text{interface}}(\mathbf{x}_n)]. \quad (5)$$

The error function which seeks to balance the linear and nonlinear voltages is written as

$$\begin{aligned} \mathbf{f}(\mathbf{x}_n) &= \mathbf{v}_{L,n} - [\mathbf{v}_{\text{NL}}(\mathbf{x}_n) + \mathbf{V}_{\text{interface}}(\mathbf{x}_n)] \\ &= \mathbf{T}\mathbf{u}_n - [\mathbf{v}_{\text{NL}}(\mathbf{x}_n) + \mathbf{V}_{\text{interface}}(\mathbf{x}_n)] \\ &= \mathbf{s}_{\text{sv},n} + \mathbf{M}_{\text{sv}}[\mathbf{i}_{\text{NL}}(\mathbf{x}_n) + \mathbf{I}_{\text{interface}}(\mathbf{x}_n)] \\ &\quad - [\mathbf{v}_{\text{NL}}(\mathbf{x}_n) + \mathbf{V}_{\text{interface}}(\mathbf{x}_n)] = 0 \end{aligned} \quad (6)$$

where

$$\mathbf{s}_{\text{sv},n} = \mathbf{T}[\mathbf{G} + a\mathbf{C}]^{-1}[\mathbf{s}_{f,n} - \mathbf{C}\mathbf{b}_{n-1}] \quad (7)$$

$$\mathbf{M}_{\text{sv}} = \mathbf{T}[\mathbf{G} + a\mathbf{C}]^{-1}\mathbf{T}^T \quad (8)$$

and  $\mathbf{u}_n$  is substituted from (5). Once this error function is balanced, the voltage across the IE,  $\mathbf{V}_{\text{interface}}$ , obtained after several nonlinear iterations per time step is converted to electric field,  $\mathbf{E} = \mathbf{V}_{\text{interface}}/\Delta$ , where  $\Delta$  represents the Yee cell spacing. In essence, when an electronic circuit is encountered at a particular Yee cell face, *fREEDA*<sup>TM</sup> will calculate the value of voltage (electric field) at that point taking into account the magnetic field (current) value provided by XFDTD and the electronic circuit components connected to that particular face.

In order to ensure that the simulators are synchronized as they step forward in time, communication is accomplished using sockets. These are fully compatible with the MPI interface, which enable massively parallel computation and full code separation between XFDTD and *fREEDA*<sup>TM</sup>. XFDTD acts as the server, while *fREEDA*<sup>TM</sup> is the client. After exchanging some preliminary handshaking signals with *fREEDA*<sup>TM</sup>, XFDTD sends the value of current across the socket at the beginning of the time step. *fREEDA*<sup>TM</sup> performs several nonlinear iterations on the electronic circuit portion of the system for that time step taking into consideration the electromagnetic current contribution, eventually returning the value of interface voltage back to XFDTD, which converts that value to electric field. Essentially, the electric field value at the interface cell is provided by *fREEDA*<sup>TM</sup> which takes into consideration the possibly complex nonlinear electrical circuit connected there, while the electric field in the rest of the electromagnetic system is updated by XFDTD using the conventional Yee algorithm. Both simulators step forward in time together, and this exchange is repeated at every time step.

### III. SIMULATIONS AND DISCUSSION

As a preliminary step, the validity of the interface was tested with some simple cases. One of the examples used was a voltage source at 1.5 GHz in series with a parallel R-C circuit feeding a monopole antenna. At first, the entire simulation was performed using XFDTD models for the above elements and

the voltage and current values at the antenna were compared with those obtained from simulating the voltage source and R-C combination in *fREEDA*<sup>TM</sup> and the monopole antenna in XFDTD. These values matched for this combination and a few other antenna and circuit combinations were found to match as well, providing a sense of confidence in the implementation of the interface.

The RF system shown in this work is a standard bilateral military SINCGARS radio which uses a double-conversion architecture and ring diode mixers. The schematic for the circuit is shown in Fig. 2. It consists of three mixer stages, each of which is a ring diode mixer, and each stage is followed by a band-pass filter. A 300 MHz input is provided by a monopole antenna simulated in XFDTD while the rest of the radio is simulated in *fREEDA*<sup>TM</sup>. The output at the third stage is designed to be a 20 MHz signal. Referring to the notation in Fig. 2, the local oscillator frequencies for a 300 MHz channel are  $f_{\text{LO1}} = 1573.12$  MHz,  $f_{\text{LO2}} = 1162.56$  MHz and  $f_{\text{LO3}} = 90.42$  MHz. Band-pass filter 2 is 30 MHz wide centered at 1273.12 MHz, Band-pass filter 3 is 1 MHz wide centered at 111.56 MHz and Band-pass filter 1 is 1 MHz wide centered at 20 MHz. The first mixer up-converts the signal so that the much higher Q's of filters at microwave frequencies can be used to realize filters with steep skirts, and the mixing elements themselves are fairly narrow band. The notch filter prevents spurious products resulting from the mixing process from being re-transmitted from the antenna.

The ring diode mixer can be a troublesome circuit to simulate because of two main reasons: firstly, the diodes represent a strong nonlinearity and the large change in current due to a small change in voltage can often result in an unstable simulation. Secondly, there is often a large difference in the signal amplitudes at the RF and the LO terminals. For example, a military radio can receive RF signals of a few femtowatts while the LO is biased at 4 V. A high-dynamic range, or the ability to detect the smallest available signal in the presence of the maximum amplitude signal without distortion, is essential. For the case of military radios, this is of the order of 140 dB. Strong nonlinearities are handled in *fREEDA*<sup>TM</sup> using parameterization techniques as explained in [10], and the high dynamic range condition is also easily satisfied [11]. A filter at the interface between the two simulators manages the dynamic range mismatch.

A fixed-step transient simulation was performed. The simulation was 200,000 time steps long with a time step of roughly 4 ps and no stability issues were encountered. Two plots are produced here, one is a snapshot of the transient output at the output terminal (designated RFG) and this is shown in Fig. 3. The frequency content at this output terminal indicates a peak at 20 MHz as shown in Fig. 4 indicating that the system is performing as designed.

### IV. CONCLUSION

Increasing complexity of communication environments, with the presence of several radios per channel and multiple

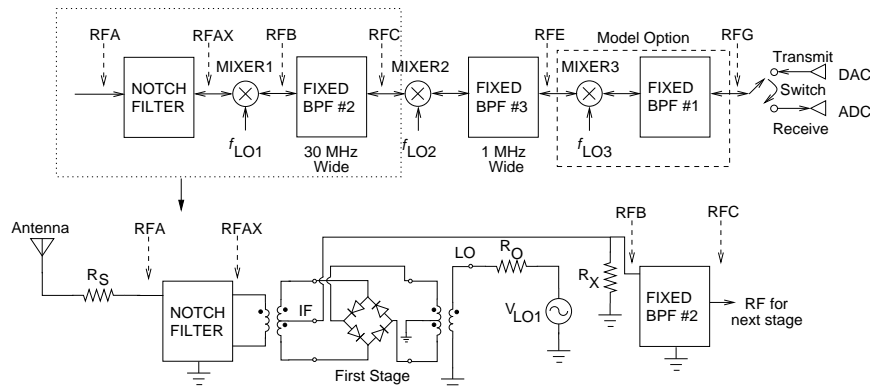


Fig. 2. SINCGARS Radio.

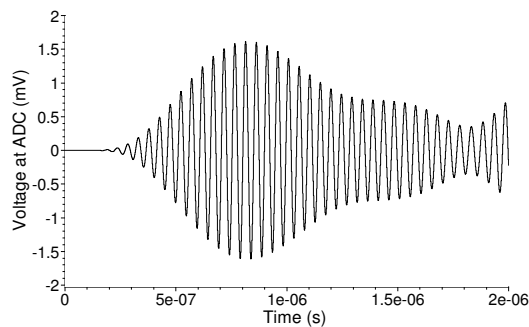


Fig. 3. Transient voltage at ADC terminal.

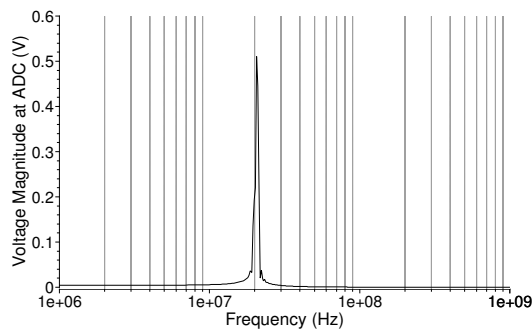


Fig. 4. Frequency content at ADC terminal.

paths, poses a challenge to the modeling of these environments. Tackling these challenges adequately requires taking into account the strongly nonlinear and dynamic characteristics of the communication equipment and accurate electromagnetic modeling of the environment in which the equipment is present. In this paper, an important step in this direction was taken by performing an EM FDTD and electronic co-simulation of a complex radio transceiver circuit. The simulation demonstrated the capability to perform a high-dynamic range nonlinear simulation. The idea is to extend this fundamental simulation capability to better understand the

nature of problems such as co-site interference and facilitate the development of co-site mitigation strategies.

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