Millimeter-wave Frequency FDTD Simulation for Error Vector Magnitude of Modulated Signals

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***Abstract*—At millimeter frequencies, a simulation of propagating complex modulated signals through an environmental channel can be computationally prohibitive using the finite difference time domain method. A transfer function approach known as the "grid impulse response" method uses a delta-function as a source signal to solve for the transfer function of the finite difference time domain grid. Once the transfer function of the channel is known, any number of source signals of differing lengths, such as those involving M-ary quadrature amplitude modulation may be used to estimate the propagation of a complex modulated signal through the environmental channel. Numerical investigations show that the maximum error between the two approaches can be very small. Simple environmental channels are used to present the error vector magnitude at mmWave frequencies obtained from the grid impulse response method.**

***Keywords*—EVM, FDTD, QAM.**

I. Introduction

Modern millimeter-wave communication systems have complex hardware and modulation schemes that can be modeled using finite difference time domain (FDTD) directly by propagating the source signal through a simulated channel. Using the full FDTD approach will be a computationally-demanding task for dense FDTD grids propagating long-duration signals due to the gridding requirements based on the very small wavelengths found at millimeter-wave frequencies. Authors in [1-2] show that transfer functions derived from the system response to a delta-function source signal can be used to predict the response of the 1D FDTD grid for an arbitrary input. Perrin *et al*. use a similar technique to predict the grid response in 3D [3]. We extend this previous work into the millimeter-wave frequencies and show numerically that a delta-function excitation of the grid can be used to obtain the transfer function of the FDTD grid. Once obtained, the transfer function can be used to solve for the signal received at any grid point when the source is excited by an arbitrary source signal. This approach is known as the grid impulse response (GIR) method. We will show the use of the GIR method to calculate the distortion of a modulated signal using error-vector-magnitude as the metric of distortion.

II. The Transfer Function and Grid Impulse Response

We define the transfer function of the FDTD grid as,

$$T(\omega) = \frac{F(\,RX(t)\,)}{F(\,TX(t)\,)}\,, \qquad (1)$$

where F is the fast Fourier transform, RX is the time-domain sampled signal at a point of interest in the FDTD grid, TX is the source signal used to excite the FDTD grid, and $T(\omega)$ is the transfer function. It is often more convenient to work with the time domain representation of the transfer function, the grid impulse response (GIR) given by:

$$GIR(t) = F^{-1}(T\,(\omega)\,)\,. \qquad (2)$$

Note that for a delta-function source signal incident on the FDTD grid, the GIR is directly obtained by sampling the grid, $GIR(t) = RX(t)$. Once the GIR is found, any signal of interest can be solved at the RX sampling point by convolution, given by:

$$RX_{calculated}(t) = GIR(t) * TX_{arbitrary}(t)\,, \qquad (3)$$

where * indicates convolution, and $RX_{calculated}$ is the predicted signal obtained from the arbitrary signal source $TX_{arbitrary}$. This formulation is most useful in solving for signals where the number of time steps needed to inject the signal into the grid is much larger than the number of time steps needed for the GIR to converge.

III. Numerical Demonstration of Accuracy

We used an M-ary quadrature amplitude modulation (M-QAM) signal to examine the accuracy of the GIR method. The FDTD code from [5] is used for all simulations, run in single precision. A source transmitting an M-QAM signal is placed in free-space terminated in either convolutional perfectly matched layer (CPML) [6] or perfect electrical conductor (PEC) boundaries. The signal is a 16-QAM modulation, 10 GSym/s, with five symbol durations. The CPML is eight cells thick. A simulation using the full FDTD approach and another using the GIR method are compared. The signals at a given point of interest in space as a function of time-step are recorded for both methods. The received signal from the full-length simulation RX_{full} is compared with the predicted signal from the GIR method. The signals are compared with an error metric defined by,

$$Error = \left|RX_{full} - RX_{GIR}\right|. \qquad (4)$$

RX_{full} has its maximum amplitude normalized to 1, and RX_{GIR} is normalized using the same normalization constant. The free space propagation case is shown in the solid line in Fig. 1. At 500 time steps, the jump in the figure is due to the arrival of the

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transmitted signal at the receiver. The signal difference previous to this time step is due to numeric noise. The GIR determination uses 1816 time steps. Through time step 1816, the error is less than 10^{-6}. At time step 1817, the error increases by ~10x, with a maximum error of approximately 10^{-3} from time step 1888 and beyond. Thus, for time steps less than or equal to the number of time steps used in the full FDTD simulation, the GIR method will capture the grid response with the error of a predicted signal $< 10^{-6}$. For time steps after this point, the error will reflect the degree to which the long-term GIR has been captured. When the GIR has begun to converge, the error for future time steps is relatively low ($\sim 10^{-3}$), and will be reduced further when the grid is sampled for more time steps. When the long-term GIR has not been captured, the error for future time steps will be large. This is shown in the dashed line in Fig. 1, where the CPML boundaries are replaced with PEC walls to simulate a metal enclosure shown by the Box results. Through the time step of the GIR simulation, the response of the grid is captured well ($< 10^{-6}$ error). The maximum error very quickly approaches 0.5 for time steps after this point, corresponding to essentially no agreement between predicted and actual signals. This is due to the resonant nature of the box, and shows the transfer function method can fail when used inappropriately.

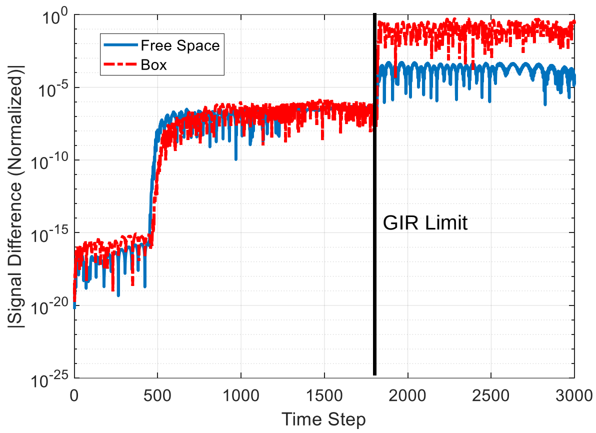

Fig. 1. Error between full-length FDTD simulation, and predicted response using the GIR method. Dashed line shows the PEC box case, while the solid line shows the free-space case. Truncated at 3000 timesteps for clarity.

IV. Error Vector Magnitude Calculation

The GIR method is an excellent compromise between accuracy and computational expense for determining distortion in a modulated signal from a channel. By creating a modulated signal and convolving with the GIR, the effects of the channel will be seen on the received signal. This can show channel effects such as path loss, power delay profile, and the error vector magnitude (EVM) [4] introduced by the channel. Application of the technique to an EVM calculation is shown using two identical dipole antennas operating at 90 GHz as a TX/RX pair in a free-space channel and in a channel with an infinite ground plane below the antennas. The distance between the two antennas is swept through 0.12 m. A 1000 symbol, duration 16-QAM signal is the excitation and the signal is post-processed to yield the EVM. The mean EVM is shown in Fig. 2. The ground-bounce case shows significantly increased distortion resulting from the reflected signal, with two distinct peaks appearing. These peaks are not present in the free-space case, and so are solely attributable to the reflected signal from the ground-plane.

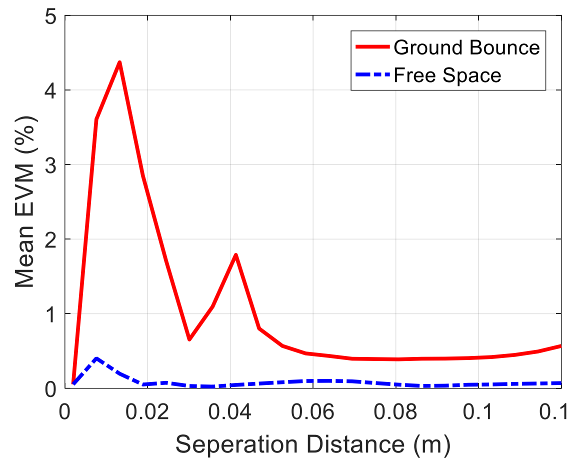

Fig. 2. EVM for a dipole-dipole case using 16-QAM signal, with results calculated by the GIR. Distinct peaks are seen from ground-bounce effects.

V. Conclusion

We have shown that the use of transfer functions in the full 3D FDTD grid can obtain long-term grid responses wit accuracy less than $< 10^{-6}$. An understanding of the error in such an approach has been introduced, showing clear cases where the GIR is not satisfactory. Through the use of the transfer function of the grid, simulations of the modulated signals can be solved rapidly, and channel effects on the EVM of the signal seen directly.

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