IEICE Communications Express, Vol.13, No.3, 56–59

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LETTER

Practical estimation and visualization of V2V propagation at 700 MHz band using FDTD method

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Abstract Herein, we present an effective analysis using the finite-difference time-domain (FDTD) method for vehicle-to-vehicle (V2V) radio propagation in the 700 MHz band at urban intersections. By combining the FDTD (2,4) method with multi-core processors, a high-precision computation and visualization analysis of the propagation phenomena is realized using practical computation resources for V2V communication systems in a large and complex propagation environment. We demonstrate that the causal relationship between the radio propagation process and reception characteristics can be analyzed both quantitatively and qualitatively.

Keywords: vehicle-to-vehicle communication, microwave, FDTD method
Classification: Antennas and propagation

1. Introduction

The development of vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), vehicle-to-network (V2N), and vehicle-to-everything (V2X) systems are accelerating toward achieving zero traffic accidents. The reception characteristics in actual driving and radio propagation environments must be analyzed to improve the performance of in-vehicle communication systems.

While higher frequencies of radio waves (e.g., millimeter waves) are used in mobile communications, the 700 MHz band, the so-called platinum frequency bands, is crucial for V2V communications.

In previous studies, both experimental and numerical approaches have been proposed to analyze V2V propagation characteristics. The experimental approach entails measuring reception characteristics (such as power level, throughput, and packet error rate) in a simple environment involving a test course with intersections [1] and measuring power-level variations in real traffic environments [2]. However, previous studies have been limited by the lack of complete control over experimental conditions, which has resulted in the low reproducibility of measurements and low spatial and temporal resolutions.

Numerical approaches have been adopted in numerous previous studies [3]owing to their high reproducibility, quantitative analysis of reception characteristics at arbitrary points, and ease of visualization of electromagnetic waves. However, when analyzing the high-frequency radio propagation of V2V communication, accurately analyzing a complex propagation environment with a large area and many radio wave scattering structures, such as buildings, roads, and trees, is highly challenging in terms of practical computational resources (amount of computer memory, computer processing speed, and computation time).

The finite-difference time-domain (FDTD) method, one of the electromagnetic-field simulation methods, solves Maxwell's equations using only mathematical approximations. Therefore, it has the advantage of being able to obtain highly accurate analytical solutions in the order of microseconds, along with the calculation steps. However, a disadvantage of the method is that the entire analysis space is divided into lattice cells sized less than 1/10th of the wavelength and are calculated sequentially, which requires substantial computational resources. Thus, a trade-off exists between the calculation accuracy and calculation resources.

To address this problem, we previously developed calculation codes for the FDTD method for a higher-order difference scheme utilizing multi-core processors, proposed a PML calculation method with reduced computational load as an alternative to CPML [4], and proposed a calculation algorithm that controls the computational timing of the analysis domain based on the progress of propagation [5].

This study describes the usefulness and effectiveness of applying the FDTD method to V2V propagation analysis in the 700 MHz band at urban intersections. In particular, this study presents: (1) compatibility of high-precision calculations and computational resource reduction, (2) visual observation of propagation phenomena in the line-of-sight and non-line-of-sight regions of V2V communications, and (3) equivalent comparison results between the analytical results of the FDTD method and field experiments.

2. Simulation condition for V2V propagation analysis

In this study, the target area for the V2V propagation analysis was a real urban intersection in Tokyo. Figure 1 shows the location of field experiments, and the replicated model of the FDTD method simulation analyses, which is the communication area required by V2V driving support services to prevent accidents during encounters. The height of the antenna on the vehicle roof was set to 2.2 m. The frequency for V2V communication was 720 MHz. The transmitter and

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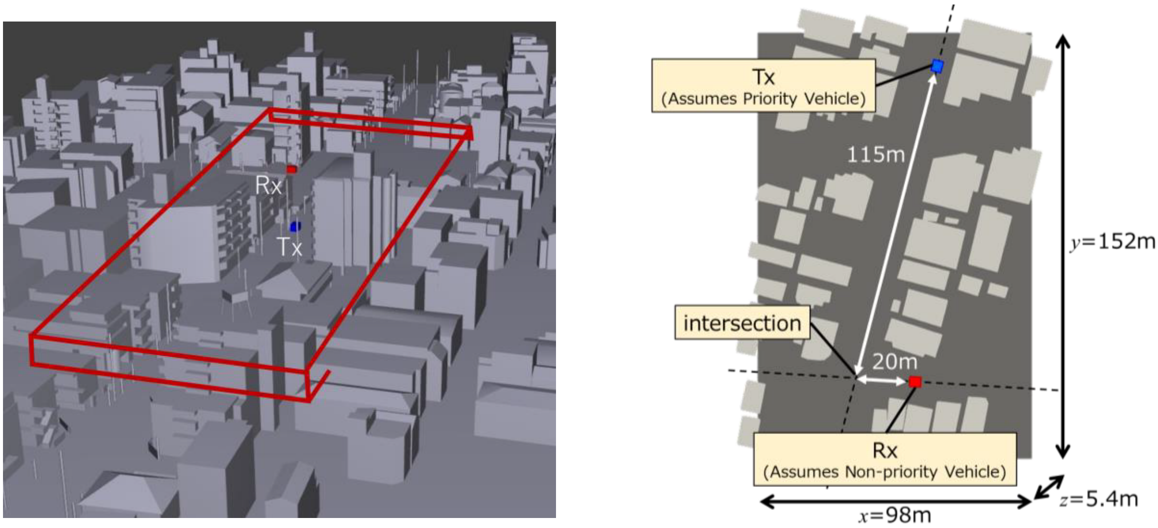
DOI: 10.23919/comex.2023XBL0153
Received November 9, 2023
Accepted December 1, 2023
Publicized January 15, 2024
Copyedited March 1, 2024



(a) Model environment (b) Transmitter and receiver position

Fig. 1 Analytical model of V2V propagation in an urban area.

receiver were located 115 m and 20 m from the intersection, respectively.

The simulation conditions of the 3-D FDTD method included a spatial resolution of 40 mm, and the time increment of 1.82×10^{-11} s, and Courant–Friedrich–Levy (CFL) stability condition of 0.136. The CFL condition was designed to reduce the total grid dispersion in all directions. The radiation source was a half-wavelength vertical dipole antenna with an applied voltage of 25 V and continuous sine wave radiation. The building and road materials of the replicated model were concrete (relative permittivity $\varepsilon_r = 15.0$, relative permeability $\mu_r = 1.0$, and conductivity $\sigma = 0.015$ S/m). The building was uniformly packed with a concrete medium. However, as this analysis focused on radio propagation at urban intersections, vehicle bodies, surrounding vehicles, pedestrians, and trees were not set up.

3. Usefulness and effectiveness using the FDTD (2,4) method

3.1 Estimation of calculation accuracy and resources in FDTD method

As the FDTD method approximates the propagation velocity in a 3-D grid cell as a constant, regardless of the propagation angle, numerical dispersion errors are inevitable. The numerical dispersion errors of the standard FDTD and FDTD (2,4) methods were obtained using Eqs. (1)–(3) [6]. $\psi_{err}(\phi,\theta)$ indicates the grid dispersion error per wavelength as the period T, the frequency f, and the speed of light c. ϕ denotes the propagation angle with the x-axis, and θ denotes the propagation angle with the z-axis.

$$\psi_{err}(\phi,\theta) = \left(\omega - \tilde{\omega}(\phi,\theta)\right)T, \tag{1}$$

$$\omega = 2\pi f, \tag{2}$$

$$\tilde{\omega}(\phi,\theta) = \frac{2}{\Delta t}\sin^{-1}\left[c\Delta t\sqrt{X^2+Y^2+Z^2}\right],$$

$$X = \frac{1}{\Delta x}\left(A\sin\left(\frac{\tilde{k}_x\Delta x}{2}\right) + \frac{1-A}{3}\sin\left(\frac{3\tilde{k}_x\Delta x}{2}\right)\right),$$

$$Y = \frac{1}{\Delta y}\left(A\sin\left(\frac{\tilde{k}_y\Delta y}{2}\right) + \frac{1-A}{3}\sin\left(\frac{3\tilde{k}_y\Delta y}{2}\right)\right), \tag{3}$$

$$Z = \frac{1}{\Delta z}\left(A\sin\left(\frac{\tilde{k}_z\Delta z}{2}\right) + \frac{1-A}{3}\sin\left(\frac{3\tilde{k}_z\Delta z}{2}\right)\right),$$

Where $\tilde{k}$ denotes the numerical wavenumber; $\tilde{k}_x = \tilde{k}\sin\theta\cos\phi$; $\tilde{k}_y = \tilde{k}\sin\theta\sin\phi$; $\tilde{k}_z = \tilde{k}\cos\theta$; and Δt indicates the temporal step, $\Delta x, \Delta y, \Delta z$ are the respective x, y, z discretization spatial steps; $A = 1$ for the standard FDTD method; and $A = 9/8$ for the FDTD (2,4) method.

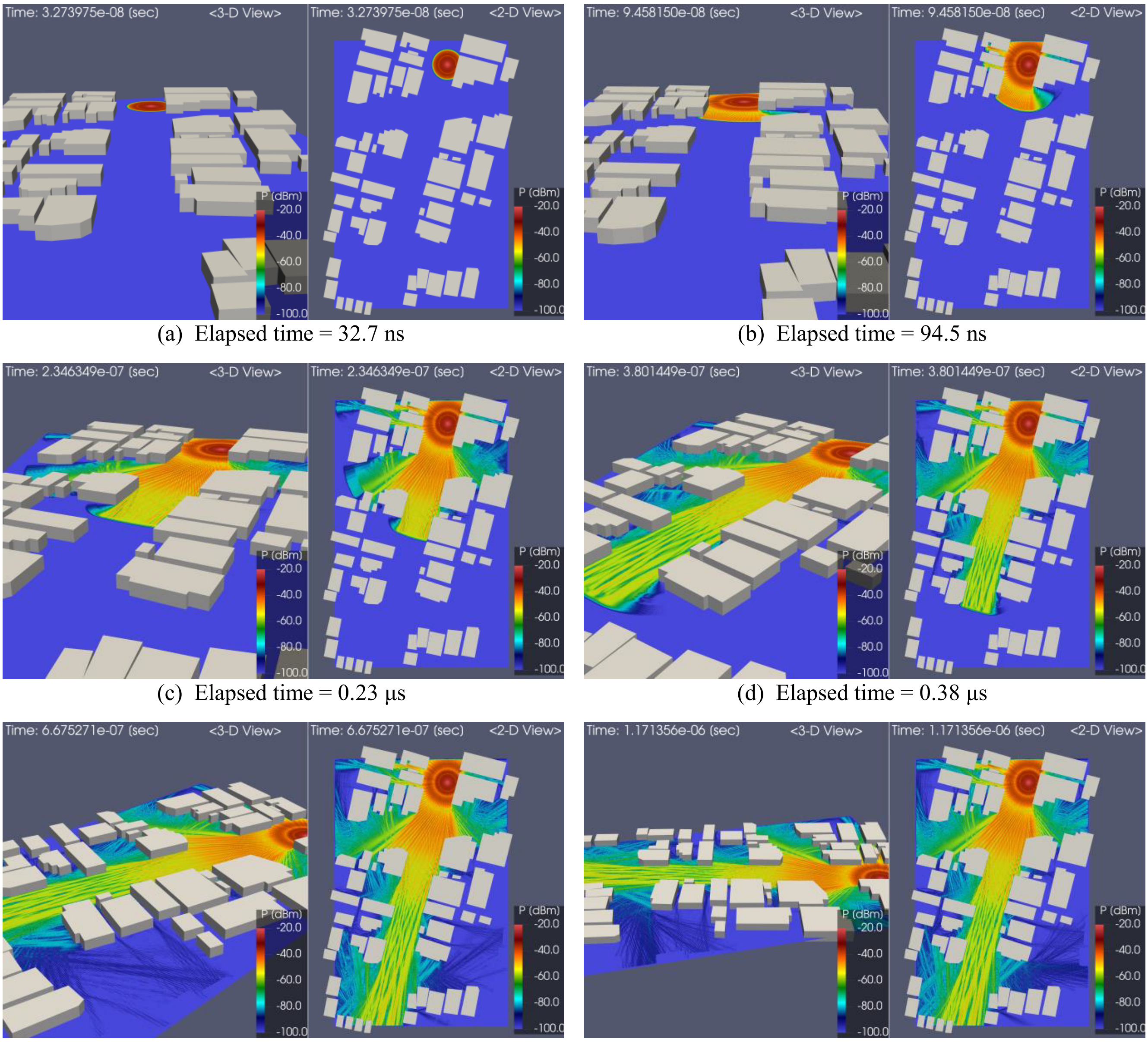
By constant, the FDTD (2,4) method balances the delay and advance of the numerical phase velocity by appropriately setting the CFL condition between 0.1 and 0.3, thereby resulting in almost no numerical dispersion errors at any propagation angle.

Therefore, the FDTD (2,4) method can be used to suppress computational resources. Additionally, the parallel processing of the FDTD (2,4) method using multi-core processors of industrial high-performance computing (HPC) can ensure practical fast computations.

3.2 Visualization results of V2V propagation in the 700 MHz band

Figure 2 shows the spatial distribution of the electromagnetic power of the V2V propagation calculated using the FDTD (2,4) method.

In the line-of-sight area, ring-shaped interference fringes around the transmitting antenna and straight interference fringes were observed along the road. The interference fringes are the result of strong interference between the direct and reflected waves from the road near the transmitting antenna. At a distance of approximately 30 m or more from the transmitting antenna, the phase difference between the direct waves and the reflected waves from the road became smaller, interference became weaker, and direct waves strongly interfered with multiple reflected waves from buildings located on either side of the road, thereby resulting in the appearance of linear interference fringes.



(a) Elapsed time = 32.7 ns
(b) Elapsed time = 94.5 ns
(c) Elapsed time = 0.23 µs
(d) Elapsed time = 0.38 µs
(e) Elapsed time = 0.66 µs
(f) Elapsed time = 1.17 µs

Fig. 2 Spatial distribution of electromagnetic power.

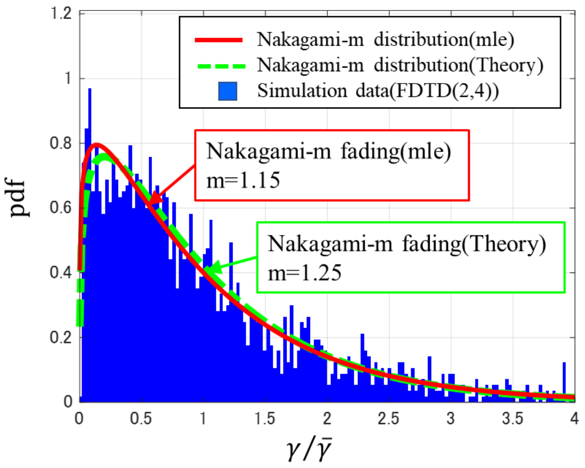
In the non-line-of-sight area, the power levels were significantly lower than those in the line-of-sight area, and the spatial distribution of the electromagnetic waves was formed by multiple streaks folded together at low power levels. This may be caused by the interference from reflected waves from the building wall at the corner of the intersection and the building wall in the non-line-of-sight area, in addition to diffracted waves from the edge of the building located at the corner of the intersection.

3.3 Comparison of calculated and experimental solutions in the probability distribution parameters of the receiving area

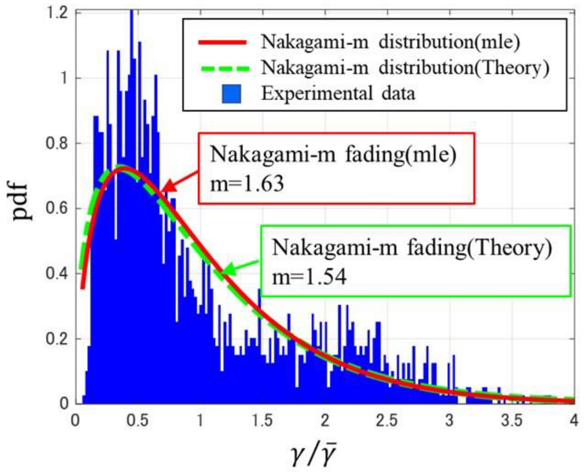
The reception fluctuation characteristics at Rx shown in Fig. 1 were compared between experimental and calculated values. The analysis area was 1.8 m × 1.8 m, which corresponds to the roof of one vehicle. The signal fluctuation characteristics of mobile communication systems are expressed using a probability density function (PDF). Figure 3 shows the PDF of the FDTD (2,4) method and the field experiments, respectively. The signal-to-noise ratio (SNR) at the received power was set as γ, with average value $\bar{\gamma}$ and normalized value $\gamma/\bar{\gamma}$.

The Nakagami-m distribution model can be expressed with respect to the SNR, as expressed in Eq. (4). The results of fitting the generic Nakagami-m distribution as the probability distribution that best expresses the fading characteristics in V2V propagation are shown as curves and superimposed [7]. Parameter m is defined by the formula shown in Eq. (4) and maximum likelihood estimation (MLE), which is an effective optimization method.

$$f(\gamma) = \frac{m^m}{\bar{\gamma}^m \Gamma(m)} \gamma^{m-1} \exp\left(-\frac{m}{\bar{\gamma}}\gamma\right)$$
$$\begin{cases} m = \dfrac{\bar{\gamma}^2}{(\gamma - \bar{\gamma})^2} \\ \gamma : \text{SNR} \end{cases} . \qquad (4)$$



(a) PDF of the FDTD (2,4) method results



(b) PDF of the experiment results

Fig. 3 Probability density function

Evidently from Fig. 3, the PDF of both results was well represented by the Nakagami-m distribution. Parameter m of the Nakagami-m distribution obtained from the FDTD (2,4) method did not differ significantly from the experimental results. In the field experiments, there were environmental changes owing to the surrounding traffic that was not fully reproduced in the simulation, which may have caused the differences in the histogram results between the experimental results and those obtained from the FDTD (2,4) method.

4. Conclusion

This study presented a multi-core computing-based FDTD (2,4) simulation and visualization that are useful and effective for understanding the V2V propagation phenomena in the 700 MHz band at real urban intersections. In particular, it presented (1) the compatibility of high-precision calculation and reduction of computational resources, (2) visual observation of propagation phenomena in line-of-sight and non-line-of-sight regions of V2V communication, and (3) equivalent comparison results between analytical results of the FDTD (2,4) method and field experiments.

Evidently, our analysis potentially leads to a causal relationship between the detailed propagation mechanisms and the reception characteristics of V2V propagation in real traffic environments.

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