On Point Source and Observation Modeling for Path Loss Calculation Using FDTD method

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1. Introduction

Body Area Network (BAN), which connects vital sensor nodes on and inside a human body wirelessly, is a promising technology for future health care [1]. Because BAN should provide reliable links, radio channel property in the vicinity to the human body should be studied intensively. Simulation using FDTD (Finite-difference Time-domain) method is one of the common approaches [2]–[6].

Simulation using FDTD, however, is technically challenging in that real antennas and a human body have different scales. Specifically, the real antennas are too small compared to the human body so that the modeling and simulation with the appropriate cell size is difficult. Although the techniques to separately simulate the antennas and the human body have been proposed [3], [4], instead of the real antennas using a point source and point receivers as infinitesimal dipoles is also informative from the viewpoint of implementation cost and generalizing the discussion as taken in [5], [6].

However, in the case of the point source and the point receivers, the calculation of the path loss from the FDTD result have not been discussed well. In this context, this paper makes three contributions: first, this paper points out the importance and the difficulty of the path loss calculation for a point source and point receivers, showing an intuitive but wrong example. Second, this paper proposes the simple and accurate path loss calculation method, which is composed of two steps: source conversion and power conversion. Third, this paper validates the proposed method analytically and by simulation.

2. BAN Channel Simulation

In the channel simulation for BAN, FDTD method is widely utilized [2]–[6]. However, this approach have the challenge that the real antennas are too small compared to the human body. If small FDTD cell size that is necessary for modeling the small antennas is applied to the human body, the number of total cell becomes too large for computation. Otherwise, only coarse modeling of simple antennas is possible.

To overcome this problem, a few techniques to separately simulate the human body and antenna have been proposed so far [3], [4]. However, those technique requires additional implementation cost. Also, assuming specific antennas makes it difficult to generalize the results. Therefore, using a point source and point receivers as infinitesimal dipoles, instead of using real antennas, is also informative as taken in [5], [6]. However, the utilization of point source and point receivers gives rise to a problem on the path loss calculation. While the path loss is an important propagation parameter from which we design the link budget of the system, the FDTD provides E-field and H-field strength. Also an infinitesimal dipole does not have a real structure, so the power calculation method for the real antennas such as [7] can not be applied.

One method, which is rather straightforward, is to take the ratio between the amplitude of E-field at the source point and the receiving points as

\[
\text{Path Loss} = \frac{|E_{\text{source}}|^2}{|E_{\text{receiver}}|^2}
\]  

(1)

In reality, this method produces huge error as shown in Figure 1, where the path loss between infinitesimal dipoles are simulated using (1) then compared with the theoretical value of the Friis transmission formula. Therefore, the method to accurately calculate the path loss is necessary.
3. Path Loss Calculation

This section proposes a path loss calculation method which has following two steps.

3.1 Source conversion

Although it is often missed in the context of the channel simulation, there are two types of a point source: a hard source and a soft source [8]. The soft source is a current source and it acts as an infinitesimal dipole whose radiated E-field strength is analytically known. On the other hand, the hard source, which physically corresponds to a voltage source in FDTD, the analytical form is not known.

In the proposed method, it is assumed to use a hard source as a point source because it is easily implemented in the same way to a delta-gap feed. Thus, the equivalent soft source (infinitesimal dipole) should be obtained from the hard source before calculating the path loss. According to [8], the hard source of E-field \( E_s(t) \) is equivalent to the soft source of current \( I_s(t) \) if the following equation is satisfied:

\[
E_s(t) = \frac{1}{3\varepsilon_0(\Delta z)^2} \int_{-\infty}^{t} I_s(t)dt
\]  

(2)

where \( \varepsilon_0 \) is the permittivity of vacuum, \( \Delta z \) is cell size, \( t \) is the current time.

If \( E_s(t) \) is realized in the same way to a delta-gap feed with a sinusoidal source, we can write

\[
E_s(t) = \frac{\sqrt{2}V \sin(2\pi ft)}{\Delta z}
\]  

(3)

where \( V \) is the r.m.s. voltage and \( f \) is the frequency. If the equivalent soft source is also assumed to be a sinusoidal source, we can write

\[
I_s(t) = \sqrt{2}I \cos(2\pi ft) \quad (0 < t), \quad I_s(t) = 0 \quad (t < 0)
\]  

(4)

where \( I \) is the equivalent r.m.s. current. Substituting (3) and (4) into (2) yields

\[
I = 6\pi f \varepsilon_0 \Delta z V.
\]  

(5)

Therefore, a sinusoidal soft source (delta-gap feed) can be converted into a sinusoidal hard source (infinitesimal dipole of which length \( L \) is same to cell size \( \Delta z \)) by just transforming the r.m.s. value using (5). Figure 2 shows the validation of this conversion by comparing the theoretical field strength of an infinitesimal dipole and the simulated result.

3.2 Power conversion

The second step for the path loss calculation is to convert E-field into transmitted power \( P_t \) and maximum receivable power \( P_r \) of infinitesimal dipoles. Assuming the linear polarization, the equation
for the conversion are expressed as

\[ P_t = \frac{2\pi}{3} \sqrt{\frac{\mu_0}{\varepsilon_0}} I^2 \left( \frac{L}{\lambda} \right)^2 \]  (6)

\[ P_r = \frac{1}{4} \frac{V^2}{R_r} = \frac{3L^2}{8\pi} \sqrt{\frac{\varepsilon_0}{\mu_0}} E^2 \sin^2 \theta_2 \]  (7)

where \( V = LE \sin \theta_2 \) is the induced voltage, \( R_r \) is the radiation resistance, \( \theta_2 \) is the angle defined as shown in Fig. 3 (a), \( \lambda \) is the wave length, and \( \mu_0 \) is the magnetic permeability of vacuum [9]. Note that \( E \) is the field strength perpendicular to the line between source and receiver, which corresponds to the so called \( E_\theta \) component radiated from the infinitesimal dipole as defined in Fig. 3 (a). Thus, if the FDTD result \( E_z \) and \( E_x \) are available as shown in Fig. 3 (b) as an example, \( E \) can be calculated by

\[ E = E_z \cos \theta_1 - E_x \sin \theta_1. \]  (8)

Therefore, using (5)-(7) the path loss can be calculated as

\[ \text{Path Loss} = P_t/P_r. \]  (9)

4. Validation

4.1 Theoretical Analysis

To validate (6)-(9) theoretically, we demonstrate that they lead to an identical equation derived from Friis transmission formula regarding infinitesimal dipoles.

First, the r.m.s. value of the radiated field strength of an infinitesimal dipole is well known as

\[ E = \eta \frac{k_0 L \sin \theta_1}{4\pi r} \]  (10)

where \( \eta = \sqrt{\mu_0/\varepsilon_0} \) is the intrinsic impedance of vacuum, \( k_0 = 2\pi/\lambda \) is the wave number, \( r \) and \( \theta_1 \) are the distance and the angle from the source dipole as defined in Fig. 3 (a) respectively. Substituting (10) into (7), we can write

\[ P_r = \frac{3}{32\pi} \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{I^2 L^2}{r^2} \sin^2 \theta_1 \sin^2 \theta_2. \]  (11)

Substituting (6) and (11) into (9) yields the path loss for infinitesimal dipoles as

\[ \text{Path Loss}_{\text{infinitesimal dipole}} = \frac{64\pi^2 r^2}{9\lambda^2 \sin^2 \theta_1 \sin^2 \theta_2}. \]  (12)

Next, the Friis transmission formula is known as

\[ P_r = \frac{\lambda^2 G_{at} G_{ar}}{16\pi^2 r^2} P_t \]  (13)

where \( G_{at} \) and \( G_{ar} \) are absolute gain of a transmitter antenna and a receiver antenna [9]. In the form of path loss, (13) can be modified as

\[ \text{Path Loss} = \frac{16\pi^2 r^2}{\lambda^2 G_{at} G_{ar}}. \]  (14)

Substituting the gain of an infinitesimal dipole [10]

\[ G_{at} = \frac{3}{2} \sin^2 \theta_1, \quad G_{ar} = \frac{3}{2} \sin^2 \theta_2 \]  (15)

into (14) leads to the path loss regarding infinitesimal dipoles

\[ \text{Path Loss}_{\text{infinitesimal dipole}} = \frac{64\pi^2 r^2}{9\lambda^2 \sin^2 \theta_1 \sin^2 \theta_2}. \]  (16)

(16) and (12) are identical, therefore, theoretically our proposed method is proven.
4.2 Numerical Simulation

To validate our approach by simulation, the path loss calculated from the FDTD result using (6)-(9) is compared with the theoretical value calculated from the Friis transmission formula. The simulation setup is summarized in Table 1. As shown in the Fig. 4, the simulated path loss matches to the theoretical value, so our approach is validated.

5. Conclusion

In this paper, we discussed how to calculate path loss in the FDTD with point source and point receivers. First, this paper pointed out the importance and the difficulty of path loss calculation for infinitesimal dipoles. Then, this paper proposed the simple and accurate path loss calculation method, which is composed of two steps: the source conversion and the power conversion. The proposed method was validated analytically and by simulation.

References


Table 1: Simulation Setup

| ∆z = L | 0.01 m (1/20λ) |
| # of cells | 60 x 250 x 250 (3λ x 12.5λ x 12.5λ) |
| Distance r | 0.2 – 2.0m (1λ – 10λ) |
| Updates | 2000 |
| Frequency f | 500MHz |
| (θ1, θ2) | (π/6, π/4), (π/6, π/4), (π/6, π/4) |
| Absorption Boundary | PML |
| 10 Layers |

Figure 4: Path Loss