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Study of Dust Effect on Radio Wave Propagation at Sub-6 GHz in Industrial Environments

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Abstract

Today, 5G wireless communication systems play an important role in the development of the Industry Internet of Things (IIoT). However, when utilizing sub-millimeter or millimeter (mmWave) waves, the existence of scatterers such as dust in the environment can cause additional path loss and may significantly degrade the system performance. In this paper, we present a split-step parabolic equation based model to characterize the effect of dust on radio wave propagation at sub-6 GHz in industrial environments.

1 Introduction

In recent years, various 5G wireless technologies have been deployed in industrial environments to improve the productivity and efficiency of industrial operation. Industrial environments have particular propagation characteristics that differ from typical indoor environments such as office or residential environments. For example, an abundance of scatterers such as dust or vapor, a source of additional and often significant path loss, could exist in a factory. To improve the reliability of wireless communication systems in industrial environments, proper radio channel characterization that can consider such effects is needed.

The parabolic equation (PE) method has been extensively applied as an efficient tool to characterize radio wave propagation in the atmosphere, underwater, and tunnel environments [1–5]. In this paper, a three-dimensional (3-D) radio wave propagation model, based on a split-step Fourier-based parabolic equation method, is presented to study the effect of dust on radio wave propagation at sub-6 GHz in industrial environments. The model utilizes the forward scattering amplitude method [6] under the Rayleigh approximation to take into account of effects of dust. Numerical results of the received power at 3.5 GHz and 4.9 GHz for cases with and without dust in a factory are studied.

2 Theory and Formulation

2.1 Dust Model

The propagation constant of a plane wave in an atmosphere filled with dust particles can be represented as [7]

$$k_v = k_0 + \frac{2\pi}{k_0}\int_0^\infty f(r)\,N(r)\,dr \tag{1}$$

where k_0 is the free-space wavenumber; $N(r)$ is the density of dust, and r is the radius of a dust particle; $f(r)$ is the forward scattering amplitude with vertical polarization. Since the size of a dust particle is relatively small, the forward scattering amplitude method [6] under the Rayleigh approximation can be applied:

$$f(r) = k_0^2\left(\frac{\varepsilon_d - 1}{\varepsilon_d + 2}\right) r^3 \tag{2}$$

where ε_d is the complex dielectric constant of dust particles. Substituting (2) into (1), we have

$$k_v = k_0 + \frac{3}{2}k_0\left(\frac{\varepsilon_d - 1}{\varepsilon_d + 2}\right)\int_0^\infty \frac{4\pi}{3} r^3 N(r)\,dr \tag{3}$$

Besides, the visibility of dust, V_d (in km), can be related with the relative mass of dust particles per cubic volume, M (in kg/m^3), as:

$$M = \rho\int_0^\infty \frac{4\pi}{3} r^3 N(r)\,dr = \frac{C}{V_d^\gamma} \tag{4}$$

where ρ is the mass particle density, and C and γ are constant parameters [8].

2.2 3-D Split-Step Parabolic Equation Method

The standard parabolic equation can be expressed as [9]:

$$\frac{\partial u}{\partial z} = \frac{1}{2jk_0}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) u \tag{5}$$

where u is the reduced plane wave solution; x and y stand for the transverse coordinates, and z is the longitudinal coordinate. Eqn. (5) can be numerically implemented using a split-step Fourier technique and fields can be updated based on a longitudinally marching procedure:

$$u(x,y,z+\Delta z) = \exp(-jk_0 m\Delta x/2)\times \\ F^{-1}\left\{C(k_x)C(k_y)F\{u(x,y,z)\}\right\} \tag{6}$$

where F and F^{-1} are the Fourier transform pair; k_x and k_y are the spectral variables, and

$$C(k) = \exp\left(\frac{-jk^2\Delta z}{2k_0}\right) \tag{7}$$

In (6), m is the modified refractivity index:

$$m = \left(\frac{k_v}{k_0}\right)^2 - 1 \tag{8}$$

where k_v can be calculated through (3).

3 Numerical Results

In this session, a factory geometry, as shown in Fig. 1, is considered. The dimensions are 10m × 10m × 100m. A horizontal unit-strength Gaussian source with a 3 dB beamwidth of 5° is placed at the center of the transverse plane at a height of 5 m. The receiver is placed at the same position along the factory.

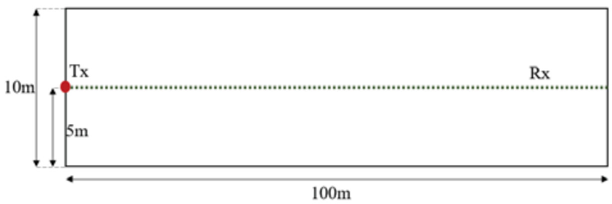

Figure 1. Diagram of the considered factory geometry.

In Fig. 2, the received power at 3.5 GHz and 4.9 GHz for cases with and without dust is compared. The values of ρ, C, and γ are chosen according to [8], where $\rho = 2.44 * 10^3$ kg/m^3, $C = 2.3 * 10^{-5}$, and $\gamma = 1.07$. The complex dielectric constant, ε_d, is chosen as $\varepsilon_d = 8-2j$, and the visibility of dust is chosen as 0.1 m. It can be observed from Fig. 2 that the dust can be a source of significant path loss in industrial environments, especially at high frequencies.

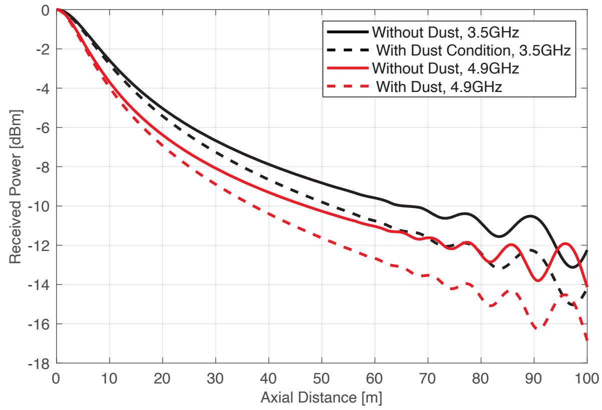

Figure 2. Received power at 3.5 GHz and 4.9 GHz for cases with and without dust in a factory geometry.

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