African Journal Of Mathematical Physics Volume **6** *(2008) 73-77*

A Local Propagation Model for Millimetric Waves

A. Jraifi[(1)], A. Khafaji[(2)], A. E Rhalami [(1)] , E.H.Saidi[(1)]
1. Canal Radio Propagation, Lab/UFR-PHE, Faculty of Science, Rabat, Morocco.
2. *Lab d'Electronique et de Télécommunication, EMI, Rabat, Morocco.*

Abstract

We propose a distribution for random rough surfaces in radio propagation channel. The modeling takes into account environment local details which cannot be ignored at millimetric waves; e.g high frequencies. The proposed radio propagation local model is done for 60 GHz frequency and goes with the advent of the millimetric systems as WLAN (Wireless Local Area Network) seen as a part of future 4G (Fourth generation) of telecommunications.

Key words: Radio propagation channel, Random rough surfaces, Wireless system, WLAN, millimetric waves.

I. INTRODUCTION

Recently, the market for wireless service has grown in a spectacular way and is the fastest growing segment of the communications industry. Wide bandwidth is available at very high frequency bands; around 60 GHz band that is at millimeter wave band $\lambda = 5mm$; and has the potential to support broadband service access [1]. In this band, the massive amount of spectral space has been allocated World-Wide for unlicensed dense wireless local communications [2]. Because of the oxygen absorption at the rate 15 dB/km [3], the signal path loss at 60 GHz is very significant and this frequency band becomes suitable for short distances where the reuse of frequencies becomes very important; especially for indoor wireless local area network (WLAN). The latter will operate in the 60 GHz band and is considered as a part of the fourth generation (4G) system [2]. This future 4G generation system includes many new types of communications systems such as broadband wireless access systems and millimeter wave LANs. However, a lot of challenges remain in designing a good wireless systems that provide the quality of service necessary to support emerging applications. Rarely the transmitter and receiver are in the direct visibility; the received signal is given by the sum of reflected waves resulting from multipaths caused by obstacles. Improvement of quality of the network service depends therefore on the good modeling of the propagation environment where details on local geometry may be no longer ignored.

A good modeling of propagation environment should take into account channel reality; in particular the roughness of the obstacle surfaces whose effect appears at millimetric waves. In this regards, recall that the Rayleigh criterion for rough surfaces reads as [4,5],

$$h > \frac{\lambda}{8cos\theta_{inc}}, \qquad (1)$$

where h, λ and θ_{inc} describe respectively the peak-to-peak height of surface, the wavelength of the electromagnetic wave and the incident angle. At 60 GHz band, the wavelength is about $\lambda = 5mm$ and for generic θ_{inc}s, one learns that most surfaces are rough. Indeed, taking the incident angle equal to $\theta_{inc} = 45°$, Rayleigh criterion requires $h(\theta_{inc}) > 0.88\ mm$ and for $\theta_{inc} = 10°$, we have $h(\theta_i) > 0.63\ mm$. Referring to these values, it comes out that all obstacle surfaces can be considered as rough surfaces for 60 GHz. It is therefore important to take into account surface roughness for a good and almost real modeling of local propagation environment.

In this paper, we develop a new theoretical model at millimetric waves with environment involving rough surfaces. The modeling takes into account local environment details which can no longer be ignored for high frequencies. The proposed radio propagation model may be used for WLAN systems considered as part of the new system 4G.

The rest of this paper is organized as follows: study of radio propagation model with an environment involving rough surfaces is given in Section 2. The new proposal distribution $\rho_c[z]$ for random rough surfaces in radio propagation channel with a theorem summarizing our results is given in Section 3. Our conclusions are drawn in Section 4.

II. RADIO PROPAGATION MODEL

In building a wireless 3-dimensional propagation model, one has to deal with the two following:
(**1**) the physical approximations to use for describing the electromagnetic signals,

$$\Psi(t,\mathbf{r}) = \int \frac{dEd^3p}{(2\pi\hbar)^4}\delta\left(E^2 - p^2c^2\right) \times$$
$$[\Psi^+ e^{-\frac{i(Et-\mathbf{pr})}{\hbar}} + \Psi^- e^{\frac{i(Et-\mathbf{pr})}{\hbar}}], \tag{2}$$

traveling between transmitters and receptors [6]. The wave Ψ is a typical electromagnetic component field obeying the usual vacuum Maxwell equation,

$$\left(\frac{\partial^2}{c^2\partial t^2} - \nabla^2\right)\Psi(t,\mathbf{r}) = 0. \tag{3}$$

Here t, r are space-time variables, $E = \hbar\omega$, $p = \hbar k$ the energy momentum of the wave and $\delta\left(E^2 - p^2c^2\right)$ is the Dirac delta function capturing the relation $E = pc$ ($k = \frac{\omega}{c}$) describing the link between energy and momentum. $\Psi^+ = \Psi^+(E,\mathbf{p})$ and $\Psi^- = \Psi^-(E,\mathbf{p})$ describe respectively the incidental and reflected waves. In space-time coordinates $\left(x^0 = ct, \mathbf{r}\right)$; the wave Ψ should be thought of as on of the four components $\sum_{\mu=0}^{3} A_\mu \epsilon_\sigma^\mu$, where A_μ is the Maxwell field and $\{\epsilon_\sigma^\mu\}$ are polarisation basis.
(**2**) the modeling of the random propagation environment by taking into account irregularities of obstacles.
Let us discuss briefly these aspects by focusing on quasi realistic environment with an obstacle represented by a random rough surface Σ.

A. Conventional Model

We begin by describing the general picture of the radio propagation system with special focus on 60 GHz frequency. Then we discuss special features on random rough surfaces and explore a way in which it can modeled.

1. Principle of system

Roughly, the device consists of a transmitter source $\mathcal{T}$, of electromagnetic waves $\Psi_{in} = \Psi_{in}(t,\mathbf{r})$, located at a given position $A(x_A, y_A, z_A)$ and a receptor $\mathcal{R}$ positioned at $B(x_B, y_B, z_B)$. As in ray tracing method, the wave $\Psi_{in}(t,\mathbf{r})$ has a definite energy momentum $(E, \mathbf{p}_A)$ and it has been represented by a ray with energy $E = \hbar\omega = 120\pi\hbar$, i.e a frequency $\omega = 120\pi\ GHz$, a momentum vector $\mathbf{p}_A = \hbar\mathbf{k}_A$ and an incident wave vector $\mathbf{k}_A$

$$\mathbf{k}_A = \frac{2\pi}{\lambda}\mathbf{u}, \qquad \lambda = 5mm. \tag{4}$$

Generally speaking, transmitter $\mathcal{T}$ and receptor $\mathcal{R}$ may be either static, $\frac{dx(t)}{dt} = \frac{dy(t)}{dt} = \frac{dz(t)}{dt} = 0$, or moving; i.e

$$\begin{aligned} v_x &= \frac{dx(t)}{dt}, \\ v_y &= \frac{dy(t)}{dt}, \\ v_z &= \frac{dz(t)}{dt}. \end{aligned} \tag{5}$$

In dynamical configuration, time evolution of the device plays then a crucial role. In this study we suppose however that $\mathcal{T}$ and $\mathcal{R}$ are fixed (time independent) and moreover not too far from each other as required by the 60 GHz band we are considering here. For WLAN for instance; the distance $|\mathbf{r}_B - \mathbf{r}_A|$ is up to few hundreds of meters.

2. Propagation environment

Along with previous device, we have a propagation environment which can be thought of as given by some real three dimensional manifold M

$$M = \begin{cases} \{a_1 \leq x \leq a_2\} \\ \{h_1 \leq y \leq h_2\} \\ \{c_1 \leq z \leq c_2\} \end{cases}, \quad (6)$$

with boundary surface $\Sigma = \partial M$ with equation defined by $f(x, y, z) = 0$ for $(x, y, z) \in M$. As a surface, Σ can be also defined in an explicit manner as

$$z = z(x, y). \quad (7)$$

In indoor propagation, M may be anything which blocks the propagation of the signal. In almost cases, it may be a material wall of width $a = a_2 - a_1$, height $h = h_2 - h_1$ and thickness $c = c_2 - c_1$. In this case, Σ is just the surface of the wall struck by the incident waves. The surface Σ describes then the obstacles for electromagnetic waves propagation preventing direct communications between transmitters and receivers. This obstacle has in general the following basic features on which depend intimately wireless propagation model building.

(**a**) Relief of Σ takes various topologies [7,8] and so has diverse representations according to type of environment (obstacle irregularities and width).

(**b**) Σ is a material surface with physical (electric, magnetic, optic) and chemical (material composition, ...) properties. These properties should be taken into account when studying interaction between waves and Σ.

Random propagation environment is generally modeled by a distribution process given by the typical Gaussian density,

$$\rho_0(\zeta) = \mathbf{N}_0 \exp\left(-\frac{\zeta^2}{2\sigma_z^2}\right), \quad (8)$$

where $\int \rho_0(\zeta)\, d\zeta = 1$ and $\mathbf{N}_0 = \frac{1}{\sigma_z \sqrt{2\pi}}$. In this Gaussian modeling, local details of the Σ geometry are then ignored. This can be explained by thinking about the above channel modeling as a first step to approach the random propagation environment. A more complete description of this environment requires taking account the following field variables,

$$\nabla z = \mathbf{e}_x \frac{\partial z}{\partial x} + \mathbf{e}_y \frac{\partial z}{\partial y}, \qquad \partial_t z = \frac{\partial z}{\partial t}, \quad (9)$$

where $\mathbf{e}_x \mathbf{e}_y = 0$ and $\mathbf{e}_x^2 = \mathbf{e}_y^2 = 1$. These variables capture the obstacle irregularities of the surface $z = z(x, y)$. Implementation of these details requires then extending the above Gaussian distribution to include local data.

In our proposal, eq(8) is modified to

$$\rho[z] = \mathbf{N} \exp\left(-\int_\Sigma \mathbf{L}(x, y)\, dxdy\right), \quad (10)$$

where $\mathbf{L}(x, y)$ is a function to be determined and where the normalization constant $\mathbf{N}$ is fixed by the constraint equation $\int \rho[z]\, dz = 1$. To fix the ideas, note that for propagation environment with static planar surface Σ with equation $z = z_0$ thought of as a rectangle with area $s = \int_0^a dx \int_0^b dy = ab$, eqs(9) are constrained as

$$\nabla z = 0, \qquad \frac{\partial z}{\partial t} = 0, \quad (11)$$

and their solution is obviously the constant $z = z_0$, which by using dimensional arguments can be read also as

$$z = \sqrt{s}\zeta, \qquad s = ab, \quad (12)$$

where ζ is defined in eq(8). The quantity $\frac{\zeta^2}{2\sigma_z^2}$ appearing in eq(8) is just the limit of the integral,

$$\frac{1}{2s\sigma_z^2} \int_\Sigma z^2 dxdy, \quad (13)$$

taken in the condition (11). Therefore the structure of the density function $\mathbf{L}(x, y)$, with $z = z(x, y)$, is

$$\mathbf{L}(z) = \frac{z^2}{2s\sigma_z^2} + ... \quad (14)$$

where the dots stand for extra terms to be given in the theorem of section 3.

B. Impact of roughness on probability density

Before captured by the receptor as $\Psi_{out}(\mathbf{r}, t) \equiv |\Psi_{out}>$, the incident wave $\Psi_{in}(\mathbf{r}, t) \equiv |\Psi_{in}>$ is generally subject to several scattering on the material surface Σ of the propagation environment. If we denote by $S = S(\theta_{in}, \theta_{diff})$ the scattering matrix of the propagation channel, we then have the following relation,

$$|\Psi_{out}> = S(\theta_{in}, \theta_{diff}) |\Psi_{in}>, \quad (15)$$

where θ_{diff} are the scattered angles. For smooth surfaces with a specular reflection eq(11), the scattered waves are generally modeled by using ray tracing method inspired from geometry optics and linear (Kirchoff) approximation [5]. At each impact point I of the incident wave, the surface Σ is replaced in Kirchoff approximation by the tangent plane at I.

For rough surfaces, which are the most common cases in reality, the local gradient ∇z of the field describing the surface Σ is not constant and eventually not defined as in the case of where Σ has singularities. In this situation, incident waves are diffracted and the above ray tracing method is no longer valid since linear approximation of geometry fails.

However, we can naively still keep the use of ray tracing method and Kirchoff approximation of planar geometries to model the random channel; provided modifying the distribution for modeling random rough surfaces as in eq(10).

In this modeling, the profile of the random surface Σ is characterized by a probability density $dP = p(z)\,dz$, i.e,

$$\frac{dP}{dz} = \mathbf{N}e^{\int_\Sigma \left[\frac{-z^2}{2\sigma_z^2}+\frac{1}{2}(\nabla z)^2\right]dxdy}, \qquad (16)$$

where the extra term $(\nabla z)^2$ captures the shape variation of Σ. In the limit eq(11), $p(z)$ reduces to the usual $\rho_0(\zeta)$ of usual Gaussian model.

III. RESULTS

Our basic results deal with the modeling of the random rough surfaces. They concern the generalization of the probability density (8) to implement the effect of roughness. These results are summarized in the following theorem:

Théorème III.1 *: **Generalized distribution***
Given a wireless propagation environment E *represented by a real three dimensional manifold M with a boundary surface $\Sigma = \partial M$; we have the following:*
*(**1**) Obstacles of incident waves are in general represented by a rough (hyper-) surface*

$$\Sigma = \{z = z(x,y,t)\}, \qquad (17)$$

embedded in three dimension real space $\mathbf{R^3}\times\mathbf{R}$. The set $\mathbf{D}\subset\mathbf{R^2}$ is a real two dimension domain with a normalized measure; $\int_\mathbf{D} dxdy = 1$.
*(**2**) Geometric roughness of the surface $z = z(x,y,t)$ is captured by the fields,*

$$grad z = \nabla\mathbf{z} \qquad (18)$$

with energy density $\frac{1}{2}(\nabla\mathbf{z})^2$.
For the case where $grad[z(x,y)]$ is constant in a local patch $\mathbf{O}_{(x,y)}$ containing the point (x,y), there is a specular reflection of the incident electromagnetic waves.
Light diffraction occurs whenever gradz is non constant on $\mathbf{O}_{(x,y)}$ or undefined.
*(**3**) Along with the geometric component $\nabla\mathbf{z}$, one has also a dynamical roughness component given by,*

$$\frac{\partial z}{\partial t} \qquad (19)$$

and describing dynamical fluctuations of the surface in the patch $\mathbf{O}_{(x(t),y(t))}$.
*(**4**) The general distribution describing random process for rough surfaces reads in the continuous variable formalism as,*

$$\rho_c[z] = \mathbf{N}e^{\int_\Sigma \left[\frac{-z^2}{2\sigma_z^2}+\frac{1}{2}(\nabla z)^2\right]dxdy}, \qquad (20)$$

where $\mathcal{N}$ is a normalization factor given by solving the condition $Trace\,\rho_c = 1$.
For quasi smooth environment, we have small variation of the geometric gradient,

$$\nabla z \sim 0 \qquad (21)$$

and small dynamical fluctuations

$$\partial_t z \sim 0. \qquad (22)$$

The corresponding factors in eq(20) may be neglected and one ends with the usual Gaussian random process described by $\rho_0 = \frac{1}{\sigma_z\sqrt{2\pi}}\exp\left(-\frac{\zeta^2}{2\sigma_z^2}\right)$.

IV. CONCLUSION

A good model of radio propagation is the key of wireless communications engineers. A knowledge of the propagation channel with rough surfaces Σ is then crucial for development of wireless system. In our study, we have highlighted a new result on roughness surfaces. Specifically, we have summarized theoretical local distribution to model local irregularities of Σ. The proposed local distribution (eq.20) takes into account roughness that appears at high frequencies; in particular at 60 GHz. The theoretical study we have developed so far goes beyond the conventional model. We think also that our study contributes to overcome the technical challenges for a better design of the radio channel. Presentation of numerical implementation of roughness at 60 GHz validating the theoretical prediction of our proposal is understudy; progress in this matter will be presented in a future occasion.

V. REFERENCES

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