Spatial characterization of propagation channels for terahertz band

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Abstract

The aim of this work consists in characterizing the Terahertz (THz) propagation channel in an indoor environment, in order to propose a channel model for THz bands. We first described a propagation loss model by taking into account the attenuation of the channel as a function of distance and frequency. The impulse response of the channel is then described by a set of rays, characterized by their amplitude, their delay and their phase. Apart from the frequency selective nature, path loss in THz band is also an others issue associated with THz communication systems. This work based on the conventional Saleh-Valenzuela (SV) model which is intended for indoor scenarios. In this paper, we have introduced random variables as Line of sight (LOS) component, and then merging it with the SV channel model to adopt it to the THz context. From simulation, we noted an important effect when the distance between the transmitter and the receiver change. This effect produces variations in frequency loss. The simulations carried out from this model show that to enhance the performance of THz system it is recommended to transmit information over transmission windows instead over the whole band.

Keywords Terahertz · Saleh-valenzuela channel modeling · LOS components · Multi-path channel · Path loss

1 Introduction

The choice of THz band is generally motivated by the fact that this band is suitable for short distance and high speed communications, with the possibility of compact and miniature systems. Thus, a network access points and a pico-cell configuration are possible. This promotes a high frequency reuse factor. On the other hand, an important concern must be done to overcome the associated challenges [1]. Indeed, millimeter systems are often confronted with problems of design and implementation and the behavior of the propagation channel at these frequencies [2].

The problems of losses, low transmission power levels, amplifier distortion of the output signal and coupling of parasitic signals can thus be very penalizing for communication over THz band. To improve the performance of terahertz channel, orthogonal frequency division

multiplexing (OFDM) was proposed by Bharathi et al. in [3]. Furthermore, to overcome the frequency selective nature of THz channel, quadrature amplitude modulation (QAM) and Quadrature Phase Shift Keying (QPSK) transmission schemes have been proposed in [4]. All these studies are based on a THz channel model to evaluate the performance of their system. Therefore, if the choice of the millimeter band is made, it is then important to choose the most efficient method to characterize the channel.

In order to evaluate the behavior of the THz wireless propagation channel, many researchers focused on one or more parameters including path-loss parameters, distance between the transmitter and the receiver, the transmitter and receiver antennas' gains, the degree of transmitter and receiver misalignment, and the power at the output of transmitter. Existing statistical models have been used in some cases to simulate the behavior of the channel. This is the case in studies [5] and [6] where the

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THz transmission channel has been statistically modeled. In [7] the measurements of channel transfer function were made using a vector network analyzer (VNA). The channel model assumes the phenomenon of ‘Clustering’ characterizing the propagation of broadband signals in multi-path environments. This study focused on the identification of clusters from the power-delay profile (PDP). The parameters of the model were extracted for the two cases LOS and non line of sight (NLOS) configurations. In [8], a frequency and an impulse response of THz channel were investigated and a wideband multiple scattering channel model for THz bands was proposed. Tsujimura et al. They focused on the full terahertz band (0.1–10.0 THz) by introducing impulse response with minimum phase as a time-domain channel model in the THz band [9]. However, they mainly focused on short-range wireless communications with a distance less than 100 cm. In [10] the impact of antenna misalignment under LOS conditions was analyzed.

The purpose of this work is to propose a detailed channel model of the THz radio channel. To do that, we are based on SV channel model. We have introduced random variables as LOS component, and then merging it with the SV channel model to adopt it to the THz context. The conventional SV channel model is used in this work thanks to its statistical nature and simplicity [11]. The proposed model is adapted in time to suit any type of use of the band allocated for THz system. Moreover, an extension of the proposed model is carried out in order to take into account the spatial and temporal fluctuations of THz channel. The modified channel model is evaluated by simulation. Indeed, simulation of transfer function and impulse response is performed by MATLAB Software. The effect of channel parameters on channel impulse response, channel transfer function and total path loss is then analyzed.

The remainder of this paper is organized as follows. Section 2 presents the Problem statement section. The proposed channel model is discussed in Sect. 3. Simulation results of the channel transfer function, the impulse response and the total path loss are demonstrated and discussed in Sect. 4. Finally, a conclusion of this paper is given.

2 Problem statement

In Frequency-Selective Channels like the case for THz frequencies, the PLE (Path Loss Exponent) is a key parameter to determine the quality of the links [12]. For this reason, we need to estimate the PLE for the efficient design and implementation of THz radio system. The PLE describes the expected loss in received power as a function of the distance between transmitter and receiver [13]. The second parameter is the losses at the reference distance $PL(D_0)$, where D_0 is the reference distance for the far field of the

antenna. Typically D_0 is between 1 and 10 m for indoor environments. The third parameter is the variations around the local average, due to the shadowing effect ζ_σ by obstacles. These parameters are defined in the standard propagation loss equation:

$$PL(D) = 10n \log_{10} \left(\frac{D}{D_0} \right) + PL(D_0) + \zeta_\sigma \quad (1)$$

Here D is the distance between transmitter and receiver, D_0 is the reference distance and n is a real number that an important effect on the propagation losses. depend on the application. In another context such as at 60 GHz [14], the value of n is of about 1.65. In UWB application with $f_c = 3.43$ GHz, the value of n is expected to be 2.01 in LOS configuration and 2.28 in NLOS configuration [15]. The PL also can be obtained from the impulse response of the channel. In this work we will examine the PL parameters based on the total loss which is obtained from channel impulse response. For this reason a THz channel model must be given. Indeed, the high path losses present in THz communication system is due to absorption by certain atmospheric particles [16]. Another challenge with THz channel is the multipath phenomena which causes interference [17]. In fact, the transmission over the (0.3–1) THz Band leads to an atmospheric attenuation of 50 dB/km for 300, 350, 410, 670 and 850 GHz [18]. In this work a modified SV channel model is used to model the THz channel. This model is used in this work because it is a suitable model to express an impulse response in an NLOS environment. To resolve this issue, we have introduced random variables as LOS component, and then merging it with the SV channel model. We demonstrated that the developed model can well approximate the transfer function and path loss results reported in [4]. Indeed, the proposed model is abridged and restricted to the azimuth angular range and the elevation angular range which permit a more accurate approximation because our model is deferent from the conventional S-V channel model, where Laplacian distribution is assumed.

3 Channel model

3.1 Wireless channel characterization

To determine the characteristics of a propagation channel, a set of impulse responses or transfer functions is analyzed to determine the PDP(τ) delay function. This part presents a number of parameters that describe different aspects of the channel.

Several analyses of the THz channel rely on a representation of the channel transfer function. In our case we are

interested in the representation of the impulse response in the form of a discrete sum of individual contribution. Each contribution, called radius, corresponds to a propagation path and has a distinct delay and complex amplitude. These representations are frequently encountered for broadband channels. In our study we will reconstruct the impulse response from the Rays. For this, we will use the formalism of Salah and Valenzuela in order to build the impulse response.

$$h(t, \tau) = \sum_{l=1}^{N_c(t)} \sum_{k=1}^{R_l(t)} \mu_{k,l}(t) e^{j\lambda_{k,l}(t)} \delta(\tau - T_l - \tau_{k,l}(t)) \quad (2)$$

where $\mu_{k,l}(t)$ represents the amplitude associated with the k th radius inside the l th cluster, $\lambda_{k,l}(t)$ is the phase corresponds to the k th radius inside of the l th cluster, $\tau_{k,l}(t)$ represents the arrival time associated with the k th radius inside of the l th cluster, $N_c(t)$ is the number of clusters, $R_l(t)$ is the number of l th cluster and $T_l(t)$ the arrival time of the l th cluster.

The PDP can be expressed by:

$$P_h(0, \tau) = \sum_{l=1}^{N_c} \sum_{k=1}^{R_l} \mu_{k,l}^2(t) \delta(\tau - T_l - \tau_{k,l}(t)) \quad (3)$$

The amplitude of the radius of the PDP usually follows a decrease close to an exponential function. This exponential decrease is observed both at the cluster level and at the radius level within each cluster. One can then define the coefficients of exponential decrease inter-and intra-cluster of the different radius, denoted respectively ρ and γ , by the following equation:

$$\mu_{k,l}^2(t) = \mu_{1,1}^2 e^{-\frac{T_l - T_1}{\rho}} e^{-\frac{T_l - T_1}{\gamma}} \quad (4)$$

These coefficients are obtained by linear regression on the PDP expressed in dB.

3.2 Modeling of the THz propagation channel

3.2.1 Spatial and temporal variations of the THz channel

Moving transmitter away from a receiver could cause significant variations in impulse response. This section describes the modeling of spatial and temporal fluctuations of the THz radio channel.

The spatial variations are due to the displacement of at least one of the transmitting or receiving antennas. Indeed, the main characteristic of the spatial variations of the channel relates to the evolution of the delay associated with each path. Thus, when the antenna moves, some propagation paths lengthen while others shorten; this phenomenon will have to be taken into account in

modeling the THz channel. The spatial variations of the THz channel have been studied very little in statistical modelling.

The evolution of the radius delays of the pulse response depends on the angle formed between the moving vector of the antenna and the radius under consideration. Specifically, it is necessary to know the direction of departure of each radius when the transmitting antenna moves, or the direction of arrival of each radius when the receiving antenna moves. In the next section, we consider the case of the displacement of the receiving antenna and we will therefore be interested in the direction of arrival of the Radius. On the other hand, for the sake of simplicity, we describe a model allowing the movement of the antenna in the plane (O, x, y), and we will take into account the azimuth ϕ of each radius. One can easily derive a three-dimensional model by including the arrival elevation of each radius.

For a baseband representation, a radius is described by its delay τ , amplitude μ and phase λ . Generating these parameters can describe the pulse response over an infinite frequency band. The generation of a simulated impulse response begins with the selection of l of clusters that compose it. When characterizing the channel, the amplitude of the different clusters follows a power-type decreasing. This approach allows a physical interpretation of the decrease of amplitude of clusters and radius, while describing more precisely the amplitude of clusters and Radius. In the following, $\mu_{1,1}$ represents the amplitude of the first radius, η is inter-cluster power decrease coefficient, T_l is the time of arrival of the l th cluster and T_1 is the time of arrival of the first cluster. We provide the following algorithms to generate cluster and radius.

$$l = l + 1 \quad (5)$$

$$T_l = T_{l-1} + \Delta T_l \quad (6)$$

$$\mu_{1,l} = \left(\frac{T_l}{T_1} \right)^{-\frac{\eta}{2}} \quad (7)$$

To validate the last cluster, its amplitude must verify the following equation:

$$20 \log \left(\frac{\mu_{1,l}}{\mu_{1,1}} \right) > -v \quad (8)$$

The arrival of the Radius will generate with the same manner as for clusters generation. In particular, within each cluster, the amplitude of the radius follows a power type decrease of the parameter ζ . To take into account the power variance observed between the first

path of each cluster and the succeeding paths, we will use the power ratio χ , expressed in dB.

$$k = 1(9) \quad (9)$$

$$\tau_{k,l} = \tau_{k-1,l} + \Delta\tau_{k,l} \quad (10)$$

$$\mu_{k,l} = 10^{\frac{\chi}{20}} \mu_{1,l} \left(\frac{\tau_{k,l} + T_l}{T_l} \right)^{-\frac{\xi}{2}} \quad (11)$$

As long as the following condition is respected, a new Radius is generated. If this condition is not respected, the generation of Radius stops.

$$20 \log \left(\frac{\mu_{k,l}}{\mu_{1,1}} \right) > -v \quad (12)$$

3.2.2 Merging loss component in SV channel model

Besides the frequency selective nature, path loss in THz band is also an others problem associated with THz communication system. THz channel express a very high molecular absorptions due to water vapor as a result of electromagnetic radiation that have high propagation loss. Thus, loss components must be considered when developing a channel model for THz bands. In this paper, we have introduced random variables as LOS component, and then merging it with the SV channel model to adopt it to the THz context. The loss component is modeled by $\gamma(f, T_k, p)$ which is the molecular absorption coefficient. In this direction, the channel impulse response is given by:

$$h(t, \tau) = \sum_{l=1}^{N_c(t)} \sum_{k=1}^{R_l(t)} \hat{\mu}_{k,l}(t) e^{j\lambda_{k,l}(t)} \delta(\tau - T_l - \tau_{k,l}(t)) \quad (13)$$

where

$$\hat{\mu}_{k,l}(t) = \mu_{1,1}^2 \frac{c}{4\pi f d} \exp \left(-\frac{1}{2} \gamma(f, T_k, p) d \right) e^{-\frac{T_l - T_1}{\rho}} e^{-\frac{T_l - T_1}{\gamma}}$$

where $\gamma(f, T_k, p)$ is the molecular absorption coefficient [3], d is the distance between the transmitter and receiver, and ρ and γ are inter-and intra-cluster of the different radius respectively.

Taking into account all peculiarities of the terahertz is the best way to develop a suitable model for THz bands. In this sense, azimuth of each radius must be considered. In the next section we will analyze the channel impulse response of by taking into account the azimuth angle.

3.2.3 Computing the impulse response of THz

3.2.3.1 The effect of displacement To calculate the impulse response on an infinite band at a point (x, y) close to the point (x_0, y_0) , it is assumed that each radius corresponds to a plane wave. Figure 1 shows the configuration obtained for a given radius. On this diagram, ϕ represents the azimuth of the incident radius and the parameters r and α verify:

$$\begin{cases} x - x_0 = r \cos(\alpha) \\ y - y_0 = r \sin(\alpha) \end{cases} \quad (14)$$

When the receiving antenna moves from the point (x, y) to the point (x_0, y_0) , the elongation of the radius Δl incident is written by:

$$\Delta l = r \cos(\phi - \alpha) \quad (15)$$

$$\Delta l = r \cos(\alpha) \cos(\phi) + r \sin(\alpha) \sin(\phi) \quad (16)$$

Which lead to

$$\Delta l = (x - x_0) \cos(\phi) + (y - y_0) \sin(\phi) \quad (17)$$

Which is equivalent to:

$$\Delta\tau_{k,l}(t) = \frac{1}{c} [(x - x_0) \cos(\phi) + (y - y_0) \sin(\phi)] \quad (18)$$

Hence, the expression of the impulse response when we take into account the displacement effect can be written as follow:

Fig. 1 variation of the length of a path when moving the antenna

$$h(x_0, y_0, \tau) = \sum_{l=1}^{N_c} \sum_{k=1}^{R_l} \hat{\mu}_{k,l}(t) e^{j\lambda_{k,l}(t)} \delta \left(\tau - T_l - \frac{1}{c} [(x - x_0) \cos(\varphi) + (y - y_0) \sin(\varphi)] \right) \quad (19)$$

3.2.3.2 Choice of the azimuth of each radius Few statistical studies taking into account the azimuth of each radius are available in the literature for the radio channel. This grouping of arrival directions into clusters has been observed in broadband channel studies. In particular, Spencer et al. proposed an extension of the Saleh and Valenzuela Model to describe the arrival azimuth of the impulse response radius [19]. In this model, the arrival azimuth of the k th radius in the l th cluster is decomposed into $\vartheta_l + \varphi_{k,l}$, where ϑ_l is the average arrival azimuth in the l th cluster. In this work, it can be considered that ϑ_l is uniformly distributed in the interval $[0, 2\pi]$. The distribution of the arrival azimuth within the cluster, $\varphi_{k,l}$, is modeled by a Laplace distribution of zero mean and standard deviation σ_φ :

$$\Psi_{k,l}(\varphi_{k,l}) = \frac{1}{\sqrt{2}\sigma_\varphi} e^{-\left| \frac{\sqrt{2}\varphi_{k,l}}{\sigma_\varphi} \right|} \quad (20)$$

We will use Spencer et al.'s model to determine the azimuth of each radius of the impulse response [19].

From the impulse response generated at the point (x_0, y_0) given by Eq. (21) and knowing the arrival azimuth of each Ray $\Phi_l + \phi_{k,l}$, one can calculate the impulse response in the following ways:

$$h(x_0, y_0, \tau) = \sum_{l=1}^{N_c} \sum_{k=1}^{R_l} \hat{\mu}_{k,l}(t) e^{j\lambda_{k,l}(t)} \delta \left(\tau - T_l - \frac{1}{c} [(x - x_0) \cos(\vartheta_l + \varphi_{k,l}) + (y - y_0) \sin(\vartheta_l + \varphi_{k,l})] \right) \quad (21)$$

Finally, the frequency response $H(x, y, f)$ is obtained by simple Fourier transform.

4 Simulation results

A series of simulations were performed using the static THz radio channel model presented in Eq. (21). For each simulation, the spatial variation model presented in section (B) was used to simulate the displacement of the transmitting antenna. Table 1 summarizes all the

Table 1 Parameters used in the simulation

Configuration	LOS
$f_{\min}$	100 GHz
$f_{\max}$	1300 GHz
Υ	50 DB
d	2, 4, 10 and 20 m
H	4.4
X	12
ξ	10.2
ΔT	13.7 ns

Fig. 2 Simulated relative power on a band from 100 to 1300 GHz. $d=4$ m (a) and 20 m (b)

parameters used to simulate the THz impulse response, the THz channel transfer function and the total path loss.

Figure 2 shows the relative power for each path, simulated over the 100–1300 GHz band. For the path (a), its length corresponds to a distance between transmitter and receiver of about 4 m, and the path (b), the length of which corresponds to the transceiver distance of about 20 m are considered in Fig. 2. From this figure, it can be observed that the short delay between two consecutive radius produces constructive or destructive interference. These interferences increase the BER (Bit Error Rate) of a transmission chain in the THz context which limits the THz system performance. Thus, it is clear that the distance has a significant effect on the relative power and consequently on the quality of the transmitted signal.

Figure 3a, b show the simulated channel transfer function, limited to the 100–1300 GHz band. This transfer function generated when a transceiver distance d of 4 m and 20 m is considered. One can clearly observe a decrease in the received power with the frequency. Thus, Fig. 3 confirms the conclusion drawn from the effect of the distance

Fig. 3 THz channel model, **a** and **b** present channel transfer function, **c** and **d** present channel impulse response

on relative power in Fig. 2. Besides, the channel transfer function in both cases expresses high attenuation. This severe attenuation can be explained by the presence of the LOS component in the THz channel. Moreover, Fig. 3c, d show the simulated channel impulse response of THz system developed in this work. It is clear from Fig. 3 that the same peaks appear for the two cases which confirm the multipath characteristics of THz channels. However, the maximum value of the amplitude is different which means that the loss component also is there. So, the proposed channel takes into account the two main characteristics of THz system which are LOS component and multipath effect.

Total path loss is another critical parameter that will be discussed in Fig. 4. In fact, the total path loss is a consequence of both spreading loss and absorption loss.

Total path loss as a function of frequency for various distance is shown in Fig. 4. We notice that, even for a distance of few meters, the total Path loss is of about 50 dB which means it highly frequency-selective. So, this high

Fig. 4 Total path loss versus frequency for LOS configuration, $d = 2$ m, 4 m, 10 m and 20 m

path loss in THz degrade the performance of the system. Also, depending on the distance, at some frequencies the path loss is too high. This high path loss present in some frequency's bands create transmission windows which are frequencies over which the path loss is fairly low. Thus, to enhance the performance of THz system it is recommended to consider transmission over these bands instead of the whole band. With increase in distance, the Total path loss increase rapidly which affect negatively the performance of the overall system due to high absorption loss. Frequency selective nature of THz channel is also another principal cause for the poor performance of the THz system. Consequently, it is recommended to use strong transmission techniques to enhance the performance of THz wireless communication system. The proposed modulation schemes must be considered over transmission windows explained above not over whole band.

The simulations result of channel transfer function and path loss of the proposed model is in good agreement with results obtained in [4]. Besides, the simulated channel impulse response expresses clearly the two main characteristics of THz bands which are the path loss and the multipath effects. Also, in this work, the path loss peaks create transmission windows which has been proved in [20, 21].

5 Conclusion

This work presents a complete model for THz radio channel. Initially, we described a path loss model for wireless channel. Then, a channel model was detailed for impulse response. This model permits generation of a set of radius by reproducing the characteristic of the impulse response such as grouping radius into clusters. Two extensions of this model have also been proposed taking into account spatial and temporal variations of the THz channel. This model can be used to design and develop the radio transceiver based on THz technology. The simulations carried out from this model show that to enhance the performance of THz system, it is recommended to consider transmission over transmission windows instead over the whole band.

As a future work, a complete channel model for THz bands can be given by taking into account other multipath effects such as shadowing. In this respect, the present work offers a guideline to study the performance of THz for short range communication. On our side, we will study the THz channel behavior in a MIMO context, because by using MIMO system the data rate can be improved without increasing the bandwidth.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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