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Research Article

Path Loss Model for Future Terahertz (THz) Wireless Communication Systems

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Abstract: Terahertz (THz) band is visualized to alleviate the capacity limitation and spectrum scarcity of the current wireless communication system. One of the major constraints for the realization of THz wireless communication is the high path loss. Terahertz band wireless communication have a very high molecular absorptions well as molecular noise generated by water vapor in response to attenuation of electromagnetic radiation that have a very high path loss propagation. Besides molecular losses communication in the terahertz spectrum has also spreading losses like reflection and scattering losses. Taking into account all these peculiarities of the terahertz radiation a proposed channel model based on ray approach is designed that accounts for terahertz wave propagation. An equivalent path loss model for terahertz multipath propagation based on ray tracing approach is developed and corroborated with the existing experimental results.

Keywords: THz, Multipath propagation, Ray-tracing, Transfer function, Cosine law, Refractive index.

1. INTRODUCTION

Data traffic of wireless communication is excessively increasing from the last few years because of far-flung use in society creates, consume and share of information. Now a day customers regularly demanding broader bandwidth and high data rate applications with the rapid growth of mobile and wireless networks [1]. The rapid increasing demand for mobile data rates and large transmission capacity for wireless communication stimulates the needs for high data rates and lager spectrum transmission technologies in future [2]. wireless capacity and data rates has seen increasing doubled every 18 months, leads to a distinct decision that 15-Gbps wireless data rate will be required in future after 10 years. Furthermore, wireless nomadic traffic and data rate capacities will be approaching that of communication in wire line systems [3, 4]. Terahertz (THz) spectroscopy becomes the most promising and emerging technique to study organic and bio-molecules [5]. The current systems and upcoming emerging systems including WLANs and UWB systems use bandwidths ranges from few MHz to several GHz. But unfortunately, these systems cannot be sufficient to provide enough larger bandwidth and very high data rates to satisfy the future need.

The large spectrum offered by the terahertz band unlocks gate to many applications that demands very high data-rates. Due to distinctive nature of THz band, the emerging applications supported by THz technology offered viable opportunities to many scientists and researchers working in different fields on a large range of subjects [6]. Some of the visualized applications at terahertz band are predicted already and with technology enhancement other will be arise very soon. The terahertz band will provide base for upcoming 5G

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cellular networks in next generation small cells [6]. Terahertz wireless communication will enable ultra-high-speed interconnection of different links. For example, optical fiber links with tablets and laptop like devices enabling high definition video conferencing and wireless distribution of huge data in data centers [7, 8]. In defense and military fields terahertz band will provide secure communication. Terahertz technology could be used in health monitoring system to gather meaningful data about patient's health [9].

Terahertz technologies are quickly advancing and the novel development of antennas and architecture of new transceivers in THz Band communication are bringing THz spectrum closer to the reality [10]. Larger-bandwidth and short-range terahertz wireless communications have been proposed for indoor communication along their standardization within the WPAN (Wireless Personal Area network) interest group EEE 802.15 [11]. There are several efficient design and development challenges in the realization of terahertz wireless communication and networks communication perspective. THz signal path loss is the major constraints for the realization of the terahertz wireless communications [9]. Materials characterization in terahertz frequency band is becoming progressively more important due to a vast variety of applications [12]. Due to absorption attenuation of oxygen molecules and water vapors in the air, THz signal experience harsh path losses that restrict the wireless communication to few meters. Wireless communication in THz band has very high molecular absorptions as well as molecular noise generated by water vapors in response to attenuation of electromagnetic radiation. Besides molecular absorption THz signals may suffer reflection and scattering losses in multipath propagation [13].

In order to realize the wireless networks in the terahertz spectrum, it is necessary to design an equivalent model that characterizes precisely the terahertz band peculiarities, requirements and constraints to be disserted for the design and analysis of terahertz band channel. Due to high spreading and molecular absorption loss in the terahertz band the pre-existing models designed for low frequency band cannot be used for terahertz spectrum because they do not attain the behavior of terahertz band [14]. The estimation of terahertz signal path loss can be determined from the particular terahertz channel transfer function. Terahertz signal short range applications already available like body scanner and medical imaging devices operating in terahertz band are applicable up to few meters. Therefore, it is necessary to design an indoor channel path loss model for future terahertz wireless propagation.Based on ray tracing technique several channel models have been verified for mm-wave frequencies through measurements to provide accurate simulation results [15].Therefore, the main focus of the paper is to design an equivalent multi-ray model for the signal path loss measurement for wireless propagation in terahertz spectrum. Terahertz signal path loss has been anticipated on the basis of different propagation scenario.

2. TECHNIQUE AND SYSTEM DESIGN

Communication in THz band can provide an extreme increase in the bandwidth but it experiences harsh path loss, thus limiting the range of THz communications. A great amount of research has been done in the past to overcome this problem by modeling the peculiarities of THz channel. In [16], a path loss model is presented for a nano-sensors network that explains the behavior of a propagating terahertz signal over plant foliage. Channel analysis, ray-tracing simulations and different propagation scenario modules are presented in [17] for THz communications. Channel model for ultra MIMO terahertz communication systems is also anticipated in [18]. Consequently, a THz channel path loss model presented in [19] for intra-body nano scale communications. In [20] the propagation channels have been characterized for different propagation scenarios. The propagation channel key components are anticipated via direct and reflected paths. All of the literature agrees that the THz communication is highly affected by the composition of medium and the distance between the transmitter and receiver. All of the above work consider high-resolution transmission molecular absorption (HITRAN) database for molecular absorption loss. As a consequence, the modeling of a THz link and to provide appropriate tools and design guidelines is a challenging task.

Provoked by the abovementioned challenges, we present a mathematical model for Terahertz signal communication link which takes into account the major peculiarities such as spreading, absorption, scattering and reflection. The equivalent path loss model for THz signal propagation is designed and simulated for line of sight scenario. We have used Friis formula and analyzed the impact of spreading loss and molecular absorption on the path loss. Reflection coefficient for smooth surfaces is characterized by Kirchhoff's scattering theory and Rayleigh roughness factor. Similarly scattering from rough surfaces are characterized by modified Beckmann-Kirchhoff's scattering theory.

For validation of our proposed model for signal path loss, the experimental measurements conducted in an office of *5.2m ×2.75m × 2.25m* walls dimensions [21] are used. All walls and ceiling are made of concrete and covered by plaster. The transmitter T_x is located just beneath the ceiling and the receiver R_x is placed in the middle of the office. For short range communication, ray tracing is the efficient technique for computing LoS, reflection and scattering components in multipath signal propagation. Case-1 is considered when there is only line of sight propagation between transmitter T_x and receiver R_x as given below in Fig. 1.

Case-2 consider terahertz signal reflection scenario in non-line of sight propagation. THz signal reflection from wall and table are considered as shown in Fig. 2.

In case-3 scenario no line of sight propagation available between T_x and R_x as shown in Fig-2. Terahertz signal scattering from rough surface of wall made of plaster and both scattering and reflection from smooth and rough surfaces of table and wall are also considered in Fig. 3.

3. LINE OF SIGHT PROPOAGATION

The channel transfer function CTF of a fixed channel when an electromagnetic signal in terahertz band travel over distance r between stationary transmitter and receiver, when there is direct path or line-of-sight communication can be represented in equation (1) as

$$H^{L.Sight}(f) = H(f).e^{-j2\pi f tL.sight} \quad (1)$$

In equation (1), f is frequency, $t^{L.sight}$ is the arrival time of terahertz signal when there is line of sight propagation at distance d between transmitter and receiver, and is given as:

where c is the light speed $c=3x10^8$ m/s the transfer function H(f) of the channel for terahertz signal line of sight propagation can be defined as the addition of both signal spreading losses

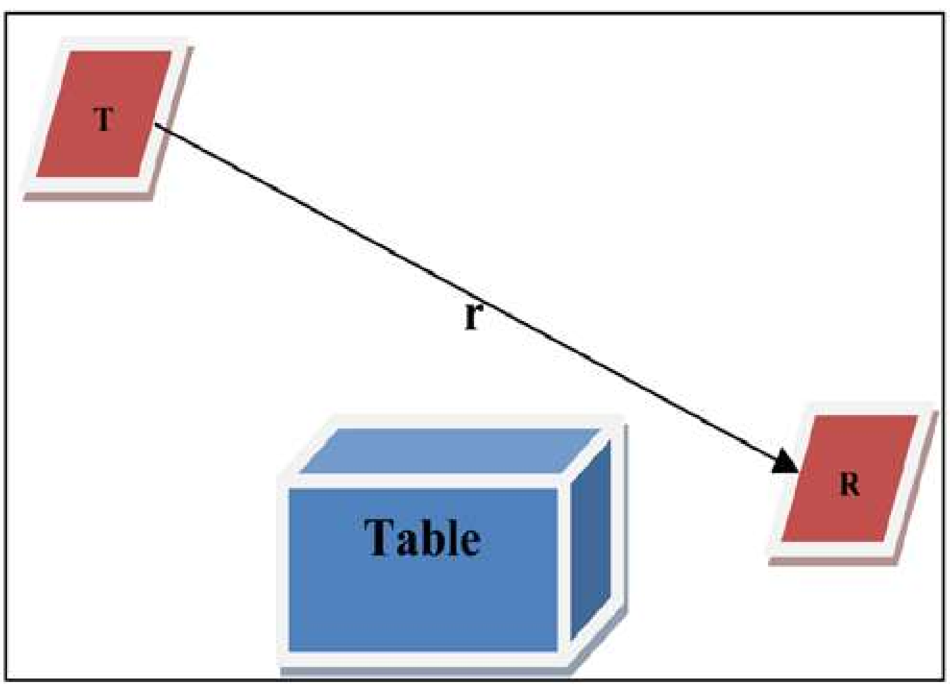


Fig. 1. THz Signal LoS Propagation Scenario

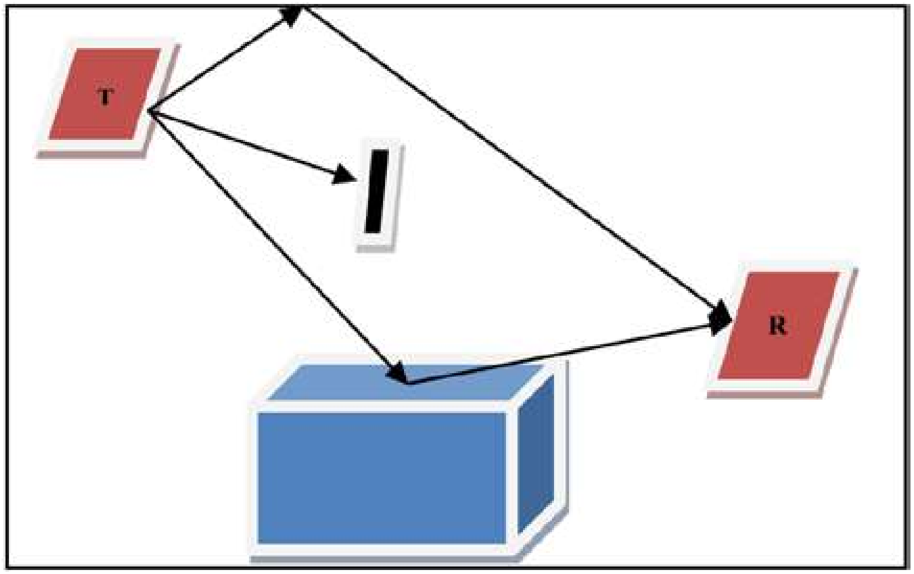


Fig. 2. THz Signal Reflection Scenario

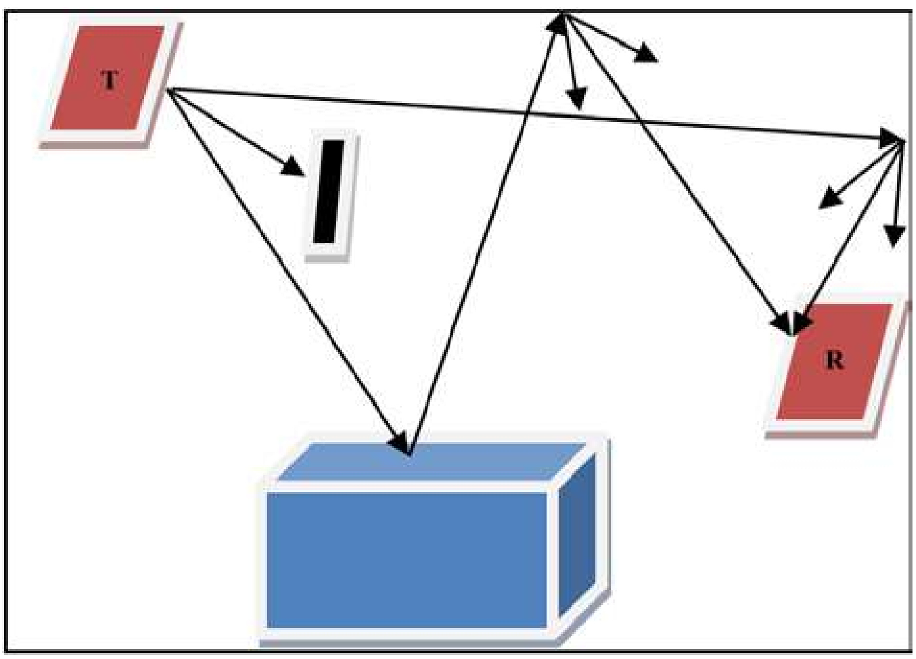


Fig. 3. THz Signal Scattering and Reflection Scenario

and atmospheric absorption losses represented in equation (2) as:

$$H(f) = H^{spread}(f).H^{abs}(f) \quad (2)$$

where $$H^{spread}(f) = \frac{c}{4\pi.f.d} \quad (3)$$

and $$H^{abs}(f) = e^{\beta(f_s)d} \quad (4)$$

Where ß is the molecular and atmospheric absorption coefficient at frequency f_s. The atmospheric loss of terahertz signal based on medium transmittance ψ can be determined with the help of Beer-Lambert law as

$$\psi(d, f_s) = \frac{P_i}{P} = e^{\beta(f_s)d} \quad (5)$$

The atmospheric attenuation coefficient ß depends upon the composition of mixture of medium gasses. Assuming office air as standard that is mainly composed of nitrogen 78%, oxygen 21% dust particles and water vapors 1%, the atmospheric attenuation coefficient ß can be determined as

$$\beta(f_S) = \sum_g \beta^g(f_S) = \beta^{NO_2}(f_S) + \beta^{O_2}(f_S) + \beta^{H_2O}(f_S) \quad (6)$$

The molecular absorption coefficient of a medium for transmitting signal having frequency f_s depends upon temperature, pressure and medium composition of the molecules. Molecular absorption coefficient can also be represented as

$$\beta(f_S) = N\eth^a(f_S) \tag{7}$$

Where ƌ is the absorbing species cross sectional area and N represents the number these species. An indoor medium absorbing molecules normal abundance can be predicted in high resolution transmission molecular absorption database HITRAN [22]. Dry air integrant natural abundances should be investigated by using water vapors volume mixing ratio. The water vapors volume mixing ratio is calculated with saturated water vapor partial pressure p^w as

$$p^w = 6.1121(1.0007 + 3.46 \times 10^{-6}p).\exp\left(\frac{17.502T}{240.97 + T}\right) \tag{8}$$

So, water vapor volume mixing ratio in presence of relative humidity is given by

$$\mu_{water} = \frac{\omega}{100}.\frac{p^w}{p} \tag{9}$$

The saturated water air Atmospheric attenuation coefficient because of these gases, dust particles and water vapors in the air can be found in detail in [23]. Also, the channel transfer function for terahertz signal molecular absorption loss in equation (2) can be determined by

$$H^{abs}(f) = e^{\beta(fs)} \tag{10}$$

4. REFLECTING SIGNAL

Terahertz Band Electromagnetic waves suffer reflection losses when reflected from rough surfaces. These reflection losses are dependent upon the shape; roughness and surface material on that electromagnetic signal have been reflected. The transfer function of the frequency dependent reflected Terahertz signal with reflected coefficient R(f) is defined in equation as:

$$H_{Ref} = R(f).A^{Abs}(f)$$

$$H_{Ref} = \frac{c}{4\pi.f.(r_1 + r_2)}.e^{\beta(fs)d}.R(f).e^{-j2\pi f\tau_{Ref}} \tag{11}$$

Here in equation (11), r_1 and r_2 is the incident and reflected path length between transceivers, and τ_{Ref} represents terahertz signal arrival time from transmitter to receiver and can be determined as:

$$\tau_{Ref} = \tau_{LoS} + \frac{(r_1 + r_2 - d)}{S} \tag{12}$$

For a smooth surface the reflection coefficient R(f) can be calculated by Kirchhoff's scattering theory as:

$$R(f) = ¥(f).\rho(f) \tag{13}$$

Here ρ(f) the Rayleigh roughness factor can be calculated as follow as in [24]

$$\rho(f) = e^{-\frac{\epsilon}{2}} \tag{14}$$

Also $$\in = \left(\frac{4\pi.f.\sigma.cos\theta_i}{c}\right)^2 \tag{15}$$

So, equation (14) now becomes

$$\rho(f) = e^{\frac{8\pi^2.f^2.\varphi^2.cos^2(\theta_i)}{c^2}} \tag{16}$$

In equation (16), θ_i is the incident wave angle, φ is the surface height standard deviation, ƛ denotes the speed of light and f is the terahertz signal frequency.

Table 1. Terahertz Signal Arrival at 0.3THz Frequency

S.No	Signal Type	Path Gain(dB)	Delay(ns)
1	LoS	-104.6	8.94
2	1st reflected ray	-112.1	9.14
3	2nd reflected ray	-113.4	9.77
4	3rd reflected ray	-116.7	10.01
5	1st scattered ray	-125.8	9.80
6	2nd scattered ray	-144.2	10.27
7	3rd scattered ray	-141.7	11.08

The surface reflection coefficient ¥(f)for incident terahertz signal reflection polarized with incident terahertz signal electric field perpendicular to the plan can be derived from Fresnel reflection equation ¥(f) can be derived by using reflection law

$$\theta_i = \theta_r \tag{17}$$

According to Snell's law

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_2) \tag{18}$$

The reflectance for incident terahertz signal polarized with electric field becomes

$$¥(f) = \left| \frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \right|^2$$

$$= \left| \frac{\cos(\theta_i) - n_t \sqrt{1 - (\frac{1}{n_t} \sin(\theta_i)^2}}{\cos(\theta_i) - n_t \sqrt{1 - (\frac{1}{n_t} \sin(\theta_i)^2}} \right|$$

$$\approx \frac{\sqrt{1 - (\frac{n_1}{n_2} \cos(\theta_t)^2}}{n_1 \cos(\theta_i) - n_2 \sqrt{1 - (\frac{n_1}{n_2} \cos(\theta_t)^2}}$$

$$\approx -(1 + \frac{-2\cos(\theta_i)}{\cos(\theta_i) + \sqrt{n^2 - sin^2(\theta_i)}}$$

$$\approx -\left(1 + \frac{-2\cos(\theta_i)}{\sqrt{n^2 - 1}}\right)$$

$$\cong -e^{-(\frac{2\cos(\theta_i}{\sqrt{n^2-1}})}$$

So

$$¥(f) = -e^{-\frac{2\cos(\theta_i)}{\sqrt{n^2-1}}} \tag{19}$$

Here in equation (19),θ_i is the terahertz signal incident angle to a rough surface, can be derived from cosine law and distance between transmitter, rough surface and receiver given by

$$\theta_i = \frac{1}{2} cos^{-1}\left(\frac{r_1^2 + r_2^2 - r^2}{2r_1 r_2}\right) \tag{20}$$

5. SCATTERING SIGNAL

Electromagnetic signal in Terahertz Band suffers diffuse scattering because of their shorter wavelengths. The scattering effect increases with the roughness level. The transfer function of the channel because of scattering effect can be expressed as: Here s1 is the separation distance between receiver and scattering point, s2 denotes the distance between scattering point and receiver. τ_scatis the scattered signal arrival time at the receiver and can be mathematically defined as:

$$H^{scat}(f) = \frac{c}{4\pi . f . (s_1 + s_2)} . e^{(-j2\pi f \tau_{scat})} . S(f) . e^{\beta(fs)} \tag{21}$$

Here s_1 is the separation distance between receiver and scattering point, s_2 denotes the distance between scattering point and receiver. τ_{scat} is the scattered signal arrival time at the receiver and can be mathematically defined as:

$$\tau_{scat} = \tau_{LoS} + \frac{(s_1 + s_2 - d)}{c} \tag{22}$$

Here τ_{LoS} is line-of-sight signal arrival time from sender to receiver and d denotes separation distance between signal transmitting point and receiver. The coefficient of scattering S(f) at large angles of incident for rough surfaces is determined by the Beckmann-Kirchhoff modified theory [25] and is given in equation (23) below as:

$$S(f) = \rho_{rough} . \Upsilon(f) \tag{23}$$

In equation (23),ϒ(f) represents Fresnel coefficient for scattered signal. The effective roughness coefficient causing scattering losses derived from [26] for rough surfaces ρ_{rough} can be determined in equation (24) as

$$\rho_{rough} = \rho_{smooth} . e^{-2k_n \varphi sin\theta_1^2} \tag{24}$$

$$\rho_{rough} = e^{\frac{8\pi^2 . f^2 . \varphi^2 . cos^2(\theta_i)}{c^2}} . e^{-2k_n \varphi sin\theta_1^2} \tag{25}$$

In equation (25), ρ_{smooth} is known as Raleigh roughness derived from [23], $k_n = \frac{2\pi}{\lambda}$ represents wave number and φ is the standard deviation of the surface. From equation (23) the Fresnel scattering coefficient ϒ(f) is given by

$$\Upsilon(f) = -e^{-\frac{2\cos(\theta_i)}{\sqrt{n^2-1}}} \tag{26}$$

Where θ_i is the incident angle and is can be calculated from cosine law, by known distance between signal transmitting and receiving point and scattering point, and expressed in equation (27) as below

$$\theta_i = \frac{1}{2} cos^{-1}\left(\frac{s_1^2 + s_2^2 - d^2}{2s_1 . s_2}\right) \tag{27}$$

Considering both reflection and scattering in non-line of sight propagation of terahertz signal through the channel, the transfer function becomes

$$H(f) = H^{scat}(f) . H^{ref}(f) \tag{28}$$

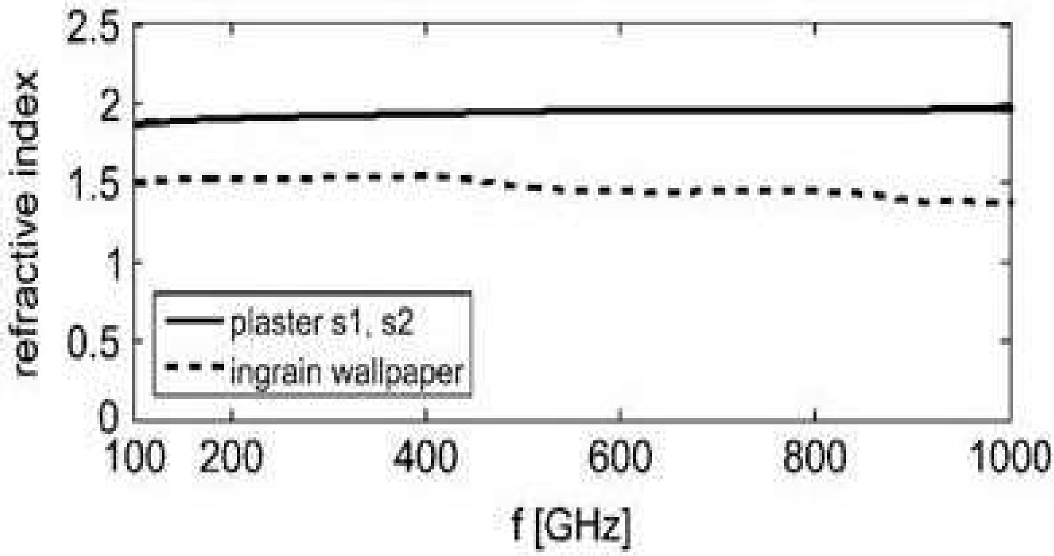


Fig. 4. Material Refractive index at THz signal

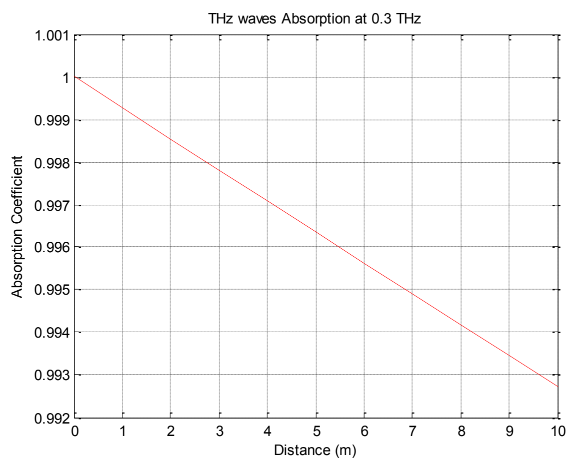


Fig. 5. Terahertz Waves Absorption Coefficient

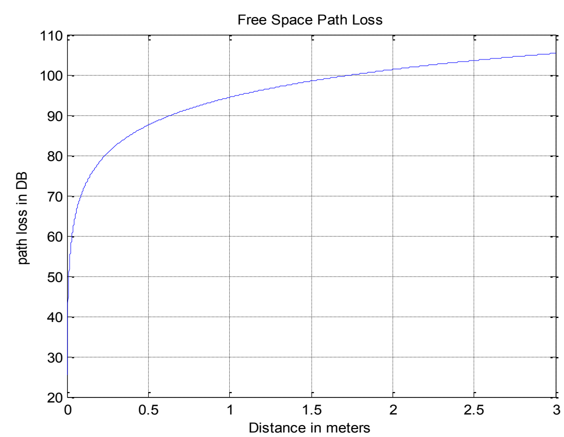


Fig. 6. Free space Path Loss in LOS Propagation

Fig. 7. THz waves reflection Coefficient

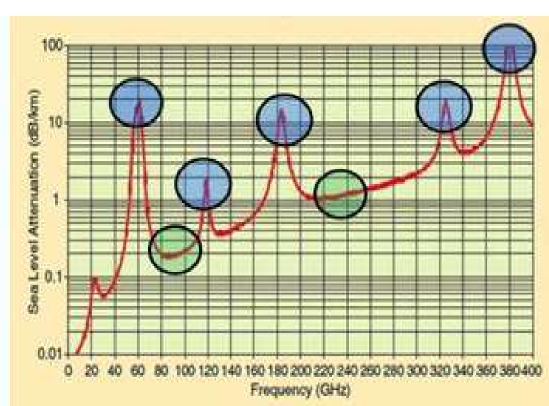


Fig. 8. Electromagnetic waves Absorption Attenuation

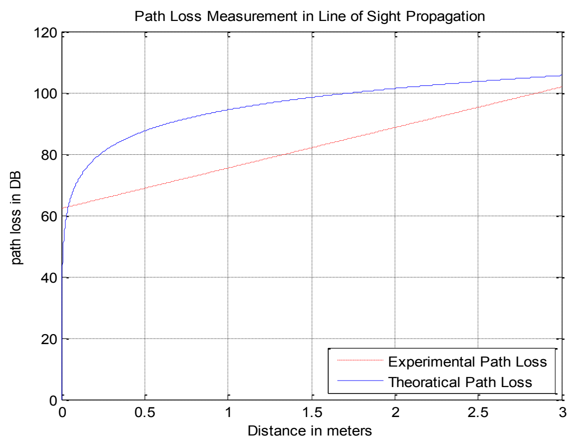


Fig. 9. THz signal LOS Path Loss Measurement

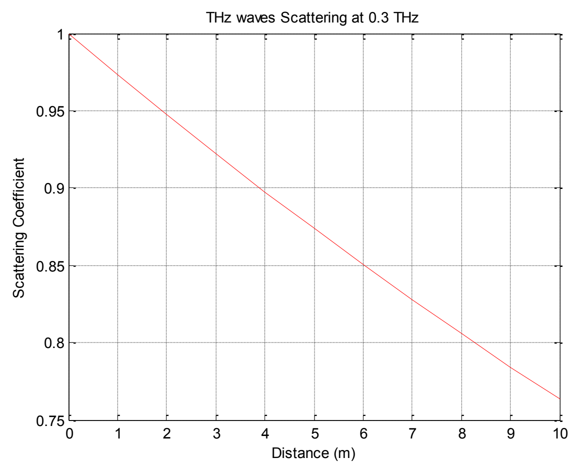
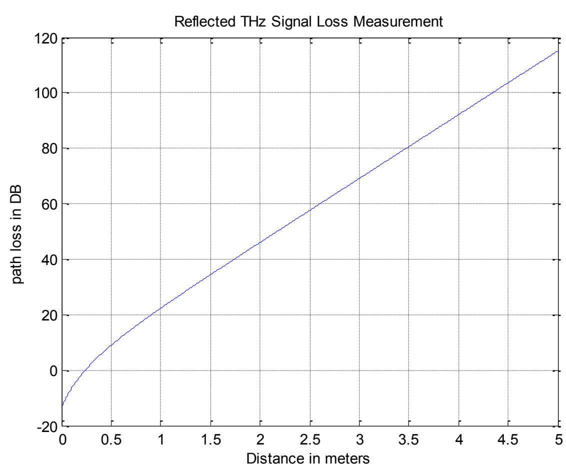
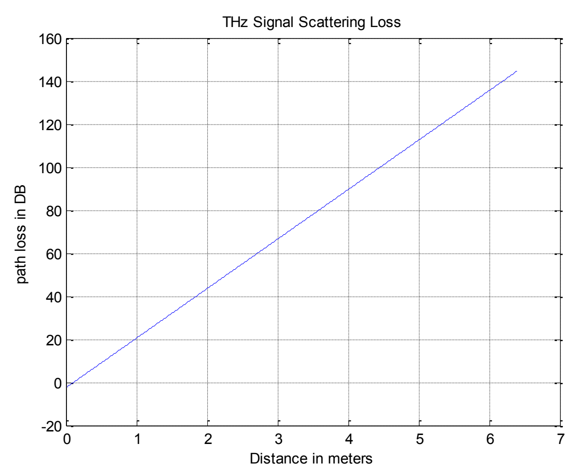


Fig. 10. THz waves scattering coefficient from rough surface



(a) Reflection loss



(b) Scattering loss

Fig. 11. THz Signal NLOS Path Loss Measurement

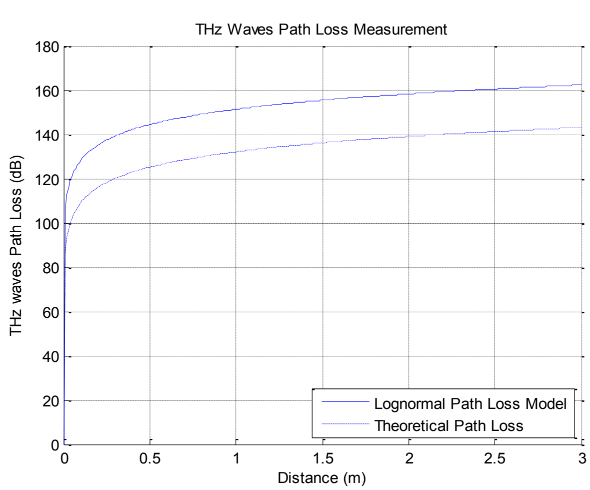


Fig. 12. Scattered THz Signal Path Loss Measurement

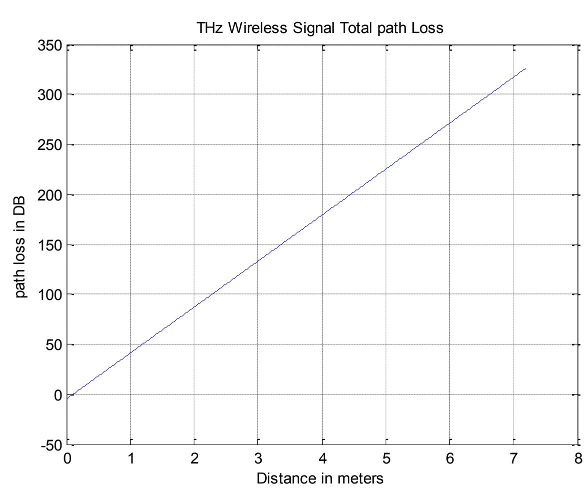


Fig. 13. THz signal Reflection and Scattering Loss

6. EQUIVALENT PATH LOSS MODEL

Now the propagation channel path loss model based on ray tracing approach that combine all the measurements of signal spreading losses, losses due to atmospheric absorption and water vapors in the atmosphere, losses due to signal scattering and reflection through different smooth and rough surfaces of table and wall as well as both scattering and reflection losses of electromagnetic signal in the Terahertz Band is proposed. Combining all the designed models about atmospheric molecular absorption losses, scattering losses and reflecting losses, a multi ray model for the ith-frequency sub-band is developed in (29) that addresses the peculiarities of the Terahertz Band.

$$H^{Eq}(f) = H^{L.sight}(f) + H^{sca}(f) + H^{ref}(f) \qquad (29)$$

7. VALIDATION OF THE PATH LOSS MODELS

Our proposed multi ray model for the measurement of terahertz signal path loss is demonstrated with the existing simulated experimental results. The experimental results simulated in [27] including type of terahertz signal at 0.3 THz arrival path, delay and path gain are outlined in Table 1. Experiment-1 is conducted for direct or line-of-sight transmission path between transmitter Tx and receiver R_x at 3m distance. While in experiment-2 no Line-of-Sight propagation between transmitter T_x and receiver R_x or terahertz signal multiple arrival paths are considered

8. RESULTS AND DISCUSSION

Terahertz signal spreading occurs by signal scattering due to collision of incident terahertz signal from smooth and rough surfaces of table and walls of indoor office channel. The free space path losses due to THz signal spreading are simulated for 3m distance between transmitter and the receiver. The absorption coefficient for THz waves propagating in the atmospheric medium are at 0.35 THz frequency at 10 m distance are simulated and is shown in Fig. 5. The distance between transmitter and reflection point is r_1 = 3.3m, reflection point and receiver distance is taken 1.7m for simulating reflection losses. Since walls and ceiling are made up bricks covered with plaster. The refractive index of plaster for 1THz colliding signal is measured 1.9 and for wood is 1.4 in [24]. The surface roughness σ which is the Rayleigh factor exponent is estimated 0.05mm for plaster and 0.12mm for wood by Gaussian distribution. An average refractive index for a medium can be approximated 1.6 at frequency f nearly equals mineral dust at frequencies of visible light [28]. Reflection coefficient for THz waves propagation at distance of 10 m and 0.3 THz frequencies are simulated and is depicted in Fig. 7. The scattering coefficient for scattered terahertz signal at 0.3THz frequency is measured where THz transmitter is fixed at incident angle $\theta_i=30^0$ to the signal scattering surface. The THz receiver sweep for angle range $\theta_2=0^0\ldots.90^0$. For all measurements for terahertz scattering as function of θ_2 , θ_3 is taken 0^0[3]. The distance between Terahertz signal transmitter T_x and surface scattering point s_1 = 3.8m, the scattering point and receiver Rx s_2 = 2.6m. The refractive index is dependent on frequencies and the medium material is assumed n = 2.1 and the surface height standard deviation φ is 0.088mm [29]. Terahertz signal free space path loss for 3m separation distance between transmitter and receiver is in Fig. 6. The atmospheric absorption at sea level causes additional losses to free space path loss of electromagnetic waves [30]. Terahertz signal free space path loss measurements including atmospheric attenuation given in Fig. 9 for line of sight propagation are very much equal to experimental measurement results performed in [31].

The scattering coefficient for THz wave propagation at 10 m distance and 0.3 THz frequencies are shown in Fig. 10. Terahertz signal reflection and scattering losses for non-line of sight propagation in indoor environment are shown in Fig. 11 (a) and (b) from smooth and rough surfaces of table and wall of office. The proposed theoretical model for scattering THz signal path loss is also compared with lognormal path loss model presented in [32] and is shown in Fig. 12. Terahertz Signal scattering and reflection or double reflection and scattering losses from smooth and rough surfaces is given in Fig. 13.

9. CONCLUSIONS

In this paper, the main constraints to wireless communications in the Terahertz spectrum are studied. We examined the line of sight free space path loss including attenuation losses, non-line of sight reflection and scattering losses impact to the wireless propagation of terahertz signal. Taking into consideration these peculiarities of the terahertz wireless communication a complete channel model based on ray tracing technique is derived. We have validated our proposed channel model through simulations in MATLAB. The simulation results show that our proposed channel path loss model is more practical and useful for interference and link budget calculations in the design of indoor wireless applications at terahertz band.

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