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Signal Path Loss Measurement for Future Terahertz Wireless Propagation Links

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Abstract**—**Terahertz Band (100GHz-10THz) offers larger bandwidth and ultra-higher data rates and is visualized as a key technology to alleviate the capacity limitation and spectrum scarcity of the currents wireless networks. There are some competent development and design challenges in the realization of wireless terahertz network. Signal high path loss is one of the major constraints for enabling wireless communication networks in the terahertz band. Thus for the consummation of wireless propagation links in the THz band an equivalent signal path loss model is designed incorporating the major peculiarities of the wireless channel that accounts for terahertz wave propagation in LoS propagation. The equivalent path loss model for terahertz LoS propagation is developed and simulated in matlab^{R}. The simulation results are compared with the lognormal path loss model results.

Keywords**—** THz, wireless channel, fading, polarizability

I. INTRODUCTION

High data rates demands in wireless data sharing are extremely grown from the past few years in our society. Customers often demand wide bandwidth and high data rates application with the rapid advancement in Wireless networks and mobile technology [1]. Wireless data rates and capacity has observed increasing every 18 month 2-fold, leads to a distinct decision that 15-Gbps data rate for wireless communication will be required after 10 years. Moreover, wireless migrant data rate capabilities will be impending towards wire-line communication systems [2]. Until now the largest connected spectrum around 60 GHz with 7 GHz available spectrum allocated for current mobile services are challenging to achieve 100 Gbps data rates. To achieve 100 Gbps data rates with realistic and spectral efficiencies of few bit/sec/Hz requires sufficiently larger bandwidth beyond 10 GHz. THz band is one of the most promising band to offer larger unregulated spectrum [3]. The current increasing demand of high dates and wireless networks can be accomplished with the allocation of higher dates and large bandwidth waves in terahertz band [4].

Terahertz frequency spectrum or so-called millimeter band ranges between 0.1 THz and 10 THz frequencies waves within electromagnetic spectrum between infrared and microwaves, with correlating wavelengths between 3 mm and 30 µm offer larger bandwidth and high data rates. Terahertz various wireless applications at short range already used in spectroscopy, imaging and remote gas sensing etc, reveals that THz band will be attractive for future larger bandwidth and higher data rates wireless communication [5]. Terahertz band applications used in security equipments at airports and other public places have high selectivity because of molecular resonance frequencies in terahertz spectrum, can penetrate through many dense materials enabling suspicious materials detection. Due to their non-ionizing nature like microwaves, terahertz radiation can be used in close vicinity to a human body [6]. It will support next generation small cells cellular networks in future [7]. Terahertz will enable interconnection of different ultra high speed links like optical fiber wire links to tablets and other wireless links. Large wireless data sharing and HD video conferencing will be enabled through terahertz technologies [8]. Terahertz networks could be used to provide secure communication in military and defense fields. Terahertz equipments could be used in health monitoring systems to gather important information about patient’s health [9].

Terahertz networks technologies are swiftly developing and the new advancement in the antennas field and transceiver architectures are bringing wireless communication in THz spectrum closer to the reality [10]. THz frequency spectrum is imagined to overcome the problems related to spectrum scarcity and capacity limitations of the current wireless communication networks. Short-range and wide bandwidth THz communications for indoor wireless communication along THz standardization have been proposed within the WPAN (Wireless Personal Area network) THz band interest group IEEE 802.15 [11], but they are considered terahertz transmission up to several meters. . One of the major constraints for the realization of the terahertz wireless communication is the high signal path loss [12]. Atmospheric absorption attenuation because of molecular absorption like oxygen molecules and water vapors in the air and high frequency propagation, terahertz signal experience harsh path loss that restrict the wireless communication to few meters [13]. In an atmospheric medium the molecular absorption influence the terahertz signals propagation [14]. Molecular absorption can be defined as the process in which some part of signal energy is converted to kinetic energy of the charged medium molecules. In addition to some other such factors like fading, spreading loss, molecular absorptions weakened the propagated signals wireless communications in the THz spectrum [5]. In this paper we proposed a path loss model for THz signal line of sight propagation incorporating the signal spreading in free space and scattering effect from particles in addition to molecular absorption in the atmospheric medium. Besides molecular absorption, molecular noises produced as a result of discharge of absorbed energy are also considered.

II. Path Loss Model

Terahertz signal path loss is the main component in the design and interpretation of wireless propagation links. The signal path loss or loss in signal strength may occur due to several effects like free space path loss or signal spreading loss, absorption losses due to signal interactions with atmospheric molecules because of molecular resonances due to oxygen and water vapors in the atmosphere. Molecules present in the atmospheric medium are energized by electromagnetic waves radiation at terahertz band. molecular noise generating when molecules in the medium discharge absorbed energy back to the medium Due to shorter wavelength terahertz signal scattering are also occur from medium molecules having size greater than propagating signal present in Los propagation of terahertz signal. Terahertz signal path loss is directly proportional propagating signal frequency, distance between transmitter and receiver and the medium composition in free space wireless communication. Terahertz signal total path loss $PL_{Total}(f,d)$ can be defined as the spreading loss function $PL_{spr}(f,d)$, absorption loss function $PL_{abs}(f,d)$, scattering loss function $PL_{scat}(f,d)$ and noise function $PL_{Noise}(f,d)$ as

$$PL_{Total}(f,d) = PL_{spr}(f,d) \times PL_{abs}(f,d) \times PL_{scat} \quad (1)$$

Terahertz signal spreading loss due to signal expansion can be calculated by Friis formula as a function of signal frequency, propagation distance and speed of light as

$$PL_{spr}(f,d) = 20\log\left(\frac{4\pi.f.d}{c}\right) \quad (2)$$

The atmospheric absorption that a propagating terahertz signal suffers due to molecular absorption over distance d depends on transmittance of the medium ψ can be determined with the help of Beer-Lambert law as

$$\psi(f) = \frac{P_i}{P} = e^{-\beta_{mole}(f_s)d} \quad (3)$$

The atmospheric attenuation coefficient β 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% [15], the atmospheric attenuation coefficient β can be determined as

$$\beta(f) = \sum_g \beta^g(f) = \beta^{NO_2}(f) + \beta^{O_2}(f) + \beta^{H_2O}(f) \quad (4)$$

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

$$\beta(f_S) = N\partial^{abs}(f_S) \quad (5)$$

Where ∂^{abs} represents the cross sectional area of the absorbing species and N represents their number. Molecules natural abundances for terahertz signal wireless channel can be predicted in high resolution transmission molecular absorption database HITRAN [16]. Dry air integrants 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 Pw as

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

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

$$\epsilon_{water} = \frac{\omega}{100}.\frac{P_w}{p} \quad (7)$$

So the moist air components abundance is given by

$$\epsilon_{moist} = \epsilon_{dry}(1 - \epsilon_{water}) \quad (8)$$

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 [12]. Also the absorption loss function $PL_{abs}(f,d)$ for terahertz signal molecular absorption loss in equation (1) can now be written as

$$PL_{abs}(f,d) = \frac{1}{\psi(f)} \quad (9)$$

$$PL_{abs}(f,d) = e^{\beta_{molec}(f)d} \quad (10)$$

The molecular noise generating due to molecular discharge energy [5] can be written as

$$PL_{Noise}(f,d) = K_B.B\big(N_L(f,d) + N_A(f)\big) \quad (11)$$

The propagating signal path loss due to molecular and particle scattering in LoS propagation medium can be calculated by using scattering coefficient [17] as inverse Beer-Lambert law as

$$PL_{scat}(f,d) = \alpha_{scat}(f)d \quad (12)$$

The scattering coefficient for number N of scattering species cross-sectional ∂^{scat} can be define as

$$\alpha_{scat}(f) = N\partial^{scat}(f) \quad (13)$$

Rayleigh scattered cross sectional areas of particles can be determined from [18] as

$$\partial^{scat}(f) = \frac{128\pi^5\beta^2}{3\lambda^4} \qquad (14)$$

The polarizability β of a molecule can be calculated [19] as

$$\beta = \frac{n(f)^2 - 1}{n(f)^2 + 2} . (\frac{x_d}{2})^3 \qquad (15)$$

From [20] the Rayleigh scatters cross sectional areas becomes

$$\partial^{scat}(f) = \frac{24\pi^3}{\lambda^4 N^2}\left(\frac{n(f)^2 - 1}{n(f)^2 + 2}\right)^2 \frac{6+3p}{6-7p} \qquad (16)$$

Where the depolarization is p and their ratio (6+3p)/(6-7p) ≈ G, the air molecules depolarization term G can be calculated from [17]. Terahertz signal scattering from a molecular particle is shown in Figure 1.

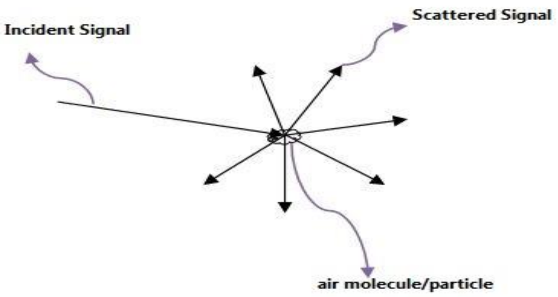

Figure 1. THz Signal Scattering form molecules/particles

The number of scattering particles can be found by log-normal distribution approximated in [21], [22] as

$$N(x_d) = \frac{dN}{dx_d} = \frac{1}{x_d\sqrt{2\pi}\ln(\sigma)} e^{\frac{-\left((\ln(x_d) - \ln(z))\right)^2}{2\ln\sigma}} \qquad (17)$$

The scattering coefficient for scattering particles can be approximated from [21] as

$$\alpha_{scat}(f) = \int_0^\infty \frac{2\pi^5 x_d^5 N}{3\lambda^4\sqrt{2\pi}\ln(\sigma)}\left(\frac{n(f)^2 - 1}{n(f)^2 + 2}\right)^2 \times e^{\frac{-\left((\ln(x_d) - \ln(z))\right)^2}{2\ln\sigma}} dx_d \qquad (18)$$

Where σ is the standard deviation, z is the scatter diameter and x_d is the scattering particle diameter.
The proposed path loss model in equation (1) for terahertz wireless propagation can be summarized as

$$PL_{Total}(f,d) = \left(\left(\frac{4\pi.f.d}{c}\right) \times e^{\beta_{molec}(f)d} \times e^{\alpha_{scat}(f)d}\right) \qquad (19)$$

Where B is the channel bandwidth, K_B represents Boltzmann constant $N_L(f,d)$ and $N_A(f)$ is the temperature of the molecular noise and other noise. Terahertz signal total attenuation coefficients for line of propagation medium can be approximated as

$$Coeff_{Total} = Coeff_{spr} + Coeff_{molec} + Coeff_{scat} + Coeff_{noise} \qquad (20)$$

III. SIMULATION RESULTS

The proposed path loss model for terahertz signal wireless propagation in LoS channel is demonstrated with the experimental results. The total path loss and attenuation coefficients are simulated for terahertz signal. Signal path loss due spreading of terahertz signal through the medium is simulated as function of THz frequencies and propagation distance in Figure 2.

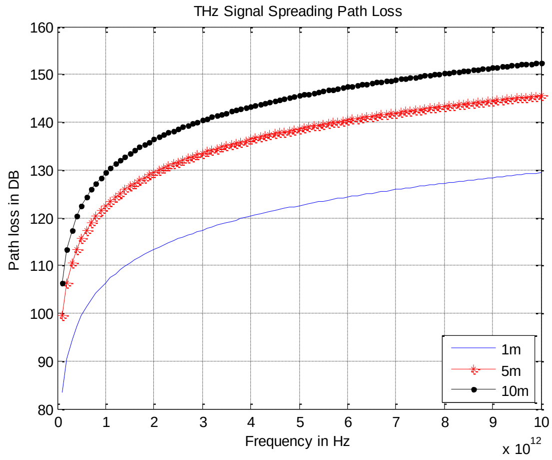

Figure 2. THz Signal Spreading Path Loss Measurement

Molecular absorption losses cause additional attenuation to electromagnetic waves in terahertz band frequencies are approximated in Figure 3. THz signal path losses due to spreading of signals are simulated in Figure 4, shows that molecular absorption loss attenuates the signal strength over distance.

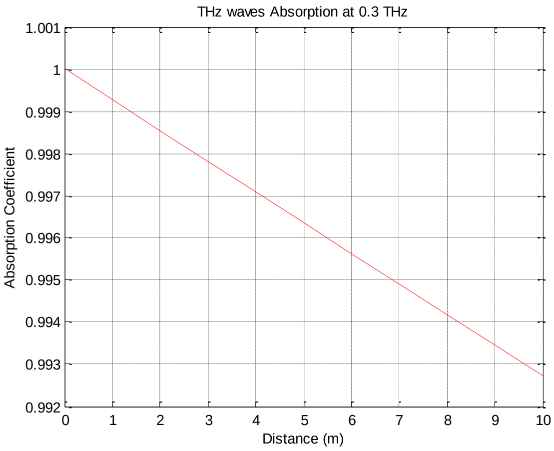

Figure 3. THz Signal molecular Absorption Loss

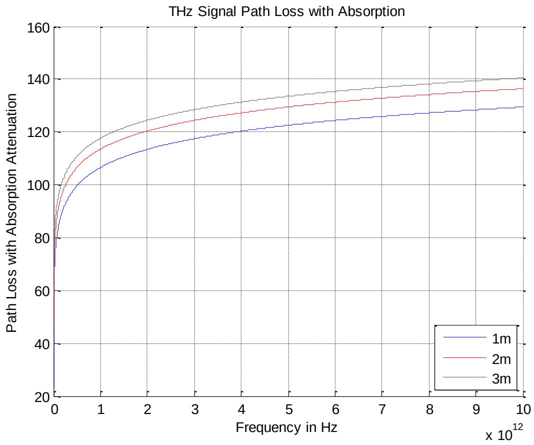

Figure 4. THz Signal Path Loss Considering Absorption

Terahertz signals wireless propagation suffers scattering through medium molecules and particles in wireless propagation. For calculating scattering coefficient the cross section of scattering particle can be calculated from $s = \frac{\pi x_d}{\lambda}$, the size of particle. Where xd is the diameter of the particle and λ is the wavelength [23]. For Rayleigh scattering the average particle size is taken 2.5um [18]. The refractive index of medium and dust n(f) is taken 1.6 for visible light frequencies [24]. The number of scattering particles per cubic cm3 is considered one million [25]. The scattering coefficient for dry air at 302.5 K temperature, 100.7 Kpa pressure and 70% relative humidity for 2um diameter and 2.7um standard deviation [26] is calculated $1.3069 \times 10^{-14} \mathrm{cm}^{-1}$. The average diameter of water droplet is (1-10um) [27]. The scattering coefficient for water vapors calculated $3.8386 \times 10^{-7} \mathrm{cm}^{-1}$. A higher frequency signals causes scattering from medium molecules because of their shorter wavelength. The scattering coefficients for high frequencies signal at 100m propagation distance are depicted in Figure 5 below.

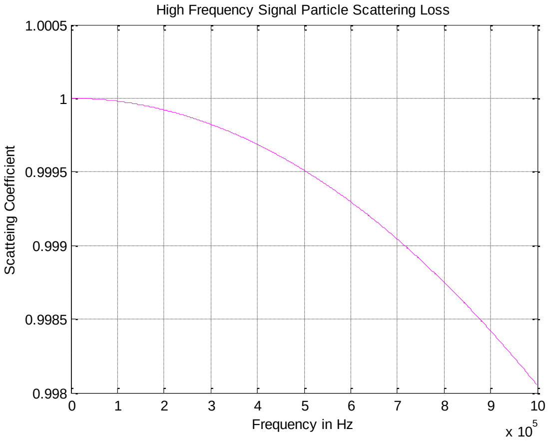

Figure 5. Scattering Coefficient for higher frequencies Signal

THz signal path loss considering free space spreading loss, molecular absorption attenuation and scattering losses due to signal scattering from particles in the medium are simulated over distance in Figure 6.

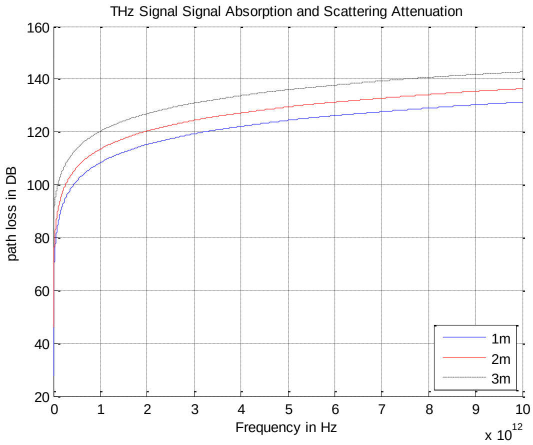

Figure 6. THz Signal Path Loss Considering Scattering

The power spectral density for molecular noise generated when atmospheric molecules re-emit absorb energy in atmospheric medium [5] as shown in Figure 7. When the atmospheric molecules re-emit the absorb energy, temperature of the channel arises causes molecular noise to THz signal wireless propagation in through the channel.

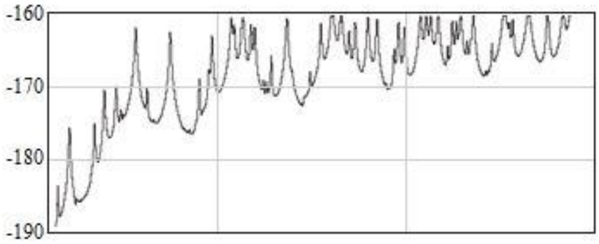

Figure 7. Molecular Noise Power Spectral Density

Finally path loss for a signal in free space wireless propagation at 0.3THz frequency are simulated for a distance of 3m including the effects of spreading loss, molecular absorption and scattering attenuation and molecular noise. The simulation results are compared with the path loss results in [28] shown in Figure 8. The simulation results are very close in value to the lognormal path loss results.

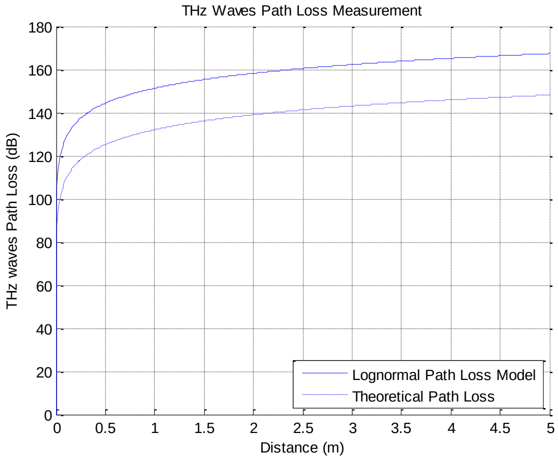

Figure 8. THz Signal Path in Los Propagation

CONCLUTION

In this paper, the main constraints to wireless communications in the Terahertz spectrum are studied. We examined the line of sight free space signal spreading including molecular absorption losses and signal scattering from medium particles. The effect of molecular noise is also considered in THz signal line of sight propagation. Taking into consideration all these peculiarities of the terahertz wireless communication an equivalent path loss model based is derived. We have validated our proposed path loss model through simulations in Matlab. The simulation results shows that our proposed path loss model is more practical and useful for interference and link budget calculations in the design of future wireless propagation link at terahertz band.

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