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Performance of terahertz channel with multiple input multiple output techniques

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Abstract: Terahertz (THz) communication is being considered as a potential solution to mitigate the demand for high bandwidth. The characteristic of THz band is relatively different from present wireless channel and imposes technical challenges in the design and development of communication systems. Due to the high path loss in THz band, wireless THz communication can be used for relatively short distances. Even, for a distance of few meters (>5 m), the absorption coefficient is very high and hence the performance of the system is poor. The use of multiple antennas for wireless communication systems has gained overwhelming interest during the last two decades. Multiple Input Multiple Output (MIMO) Spatial diversity technique has been exploited in this paper to improve the performance in terahertz band. The results show that the Bit Error Rate (BER) is considerably improved for short distance (<5 m) with MIMO. However, as the distance increases, the improvement in the error performance is not significant even with increase in the order of diversity. This is because, as distance increases, in some frequency bands the signal gets absorbed by water vapor and results in poor transmission. Adaptive modulation scheme is implemented to avoid these error prone frequencies. Adaptive modulation with receiver diversity is proposed in this work and has improved the BER performance of the channel for distance greater than 5 m.

Key words: terahertz communication, channel modeling, line of sight (LOS), non line of sight (NLOS), bit error rate(BER), multiple input multiple output (MIMO), receiver diversity

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Introduction

Wireless data rates have doubled every eighteen months over the last thirty years[1]. New technologies have been constantly evolving to support the demand for high data rate. Advanced modulation schemes and signal processing techniques in the physical layer increased the spectral efficiency of the current wireless communication systems[2-3]. However, the spectrum scarcity of the present day communication systems put an upper bound for the achievable data rates. One of the feasible solutions to overcome the spectrum scarcity and achieve high data rate is to use terahertz band of frequency for communication purpose[1-4]. This technology improves the achievable data rate to Terabit-per-second (Tbps). THz band ranges from 0.1 to 10 Terahertz and the corresponding wavelength from 3 000 to 30 μm[1,3]. Communication over this ultra broadband frequency poses technical challenges in both from communication perspective and from the device design and development. However, the advancements in the development of transceiver and antenna systems are rapidly bringing the THz communication into reality[4-6]. THz communication will facilitate a range of application starting from high speed 5G communication to nanonetworks. Nanonetworks include diversified range of applications from healthcare to home security. The feasibility of THz communication for WLAN application is explored in Ref. [7]. The usefulness of THz communication in nanonetworks has been highlighted in Refs. [1-6].

THz waves, located between millimeter and infrared waves are highly absorbed by water vapors present in the atmosphere. This results in high path loss and limits the communication distance. Model of both LOS and NLOS paths in THz frequency have been researched extensively in the recent past. LOS propagation model for the THZ band was developed and analyzed in Refs. [8-9]. Molecular absorption and spreading loss are the major factors in LOS path. The model of NLOS path must account for the reflection of electromagnetic waves at obstacle[10]. The reflection characteristics depend on the material[11-12]. In Refs. [9,13] the multipath THz channel including LOS and NLOS propagation paths has been developed using raytracing simulation. The capacity of the THz channel considering a single transmission window of almost 10 THz wide has been investigated in Ref. [8]. With increase in distance, performance degrades rapidly due to high absorption loss. To overcome this, adaptive modulation schemes has been proposed[14], where transmission

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windows are used for transmission instead of entire band.

In this paper, multipath channel model for THz channel is developed and the BER performance of this channel has been investigated with BPSK modulation scheme for various distances. From the simulation results, it is understood that for a distance of >5 m, the performance of the channel is not good. To overcome this, spatial diversity techniques in terms of number of antennas has been proposed in this work.

Multiple antennas can be utilized in order to accomplish a multiplexing gain, a diversity gain, or an antenna gain, thus enhancing the bit rate, the error performance, or the signal-to-noise-plus-interference ratio of wireless systems, respectively[16-17]. Conventional single-antenna system obtains optimal performance by exploiting the time domain and/or the frequency domain. Employing multiple antennas, exploits the spatial domain to maximize the system performance. In this work receiver diversity techniques[19] with Maximal Ration combining (MRC) have been explored and the performance of the system is analyzed. Use of multiple antenna increases the system performance for small distance. However for a distance greater than 5 m, improvement in performance is insignificant. For such cases adaptive modulation with MIMO is proposed and is shown that this technique improves the performance of the system for larger distance.

Section II of this paper describes LOS and NLOS channel modeling. The performance analysis of THZ channel using BPSK is studied in Section III. Section IV introduces diversity techniques for improving the performance of the system. Adaptive modulation scheme with diversity technique is discussed and analyzed in Section V. Concluding Remarks are highlighted in section VI.

1 Channel model

A model of THz channel is developed considering both Line of Sight (LOS) and Non Line of Sight (NLOS) propagation paths. LOS path is highly influenced by the molecular the absorption which is a strong function of the gas molecules present in the atmosphere. The gas molecules resonate in this frequency range and absorb the signal energy propagating through them[1-3]. The absorption coefficient of different gas molecules in the atmosphere ($\alpha_{mol}(f,t_k,p)$) can be computed using the High Resolution Transmission (HITRAN) data base. HITRAN is a compilation of spectroscopic parameters used to predict and simulate the transmission, absorption and emission of light through gaseous media[15]. Absorption coefficient is also a function of frequency, temp erature and pressure. Figure 1 shows the absorption coefficient as a function of wavenumber starting from 3.3 cm^{-1} to 50 cm^{-1} (0.1 THz to 1.5 THz) for two different temperatures 293 degree Kelvin (20℃) and 303 (30℃) degree Kelvin. Pure water vapor is considered as the atmospheric gas. Absorption coefficient is slightly higher for lower temperature but they follow a similar pattern for both temperatures peaking at some frequencies. Absorption peaks occurs at wave numbers 19 cm^{-1}, 25 cm^{-1}, 33 cm^{-1}, 37～42 cm^{-1} and 47 cm^{-1} corresponding to frequency 0.55 THz, 0.74 THz, 0.98 THz, 1.09 to 1.25 THz and 1.41 THz.

The absorption loss of the electromagnetic wave with

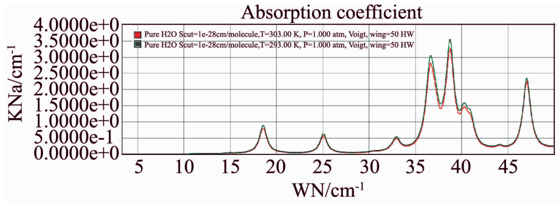

Fig. 1 Absorption coefficient of water vapor

frequency propagating over a distance is[9]

$$A_{abs}{}^{dB}(f,r) = \alpha_{mol}(f,T_k,p)\,r\,20\log e \quad .(1)$$

As electromagnetic waves propagate through the medium it gets expanded which results in spreading loss. Spreading loss depends on the distance and is defined as

$$A_{spread}{}^{dB}(f,r) = 20\log_{10}\frac{(4\pi fr)}{c} \quad ,(2)$$

where, $c=2.9979\times10^8$ m/s is the speed of light.

The total LOS path loss is the result of both absorption loss and spreading loss and is given as,

$$A_{dB}(f,r) = A_{abs}dB(f,r) + A_{spread}dB(f,r) \quad .(3)$$

LOS path loss as a function of frequency for various distance is given in Figs. 2(a) and 2(b) for 20℃ and 30℃ respectively. Path loss is highly frequency-selective and is 100 dB even for a distance of few meters. Depending on the distance and the composition of the gas mixture in the atmosphere, at some frequencies the path loss is too high. This high path loss in certain frequencies forms transmission windows[14].

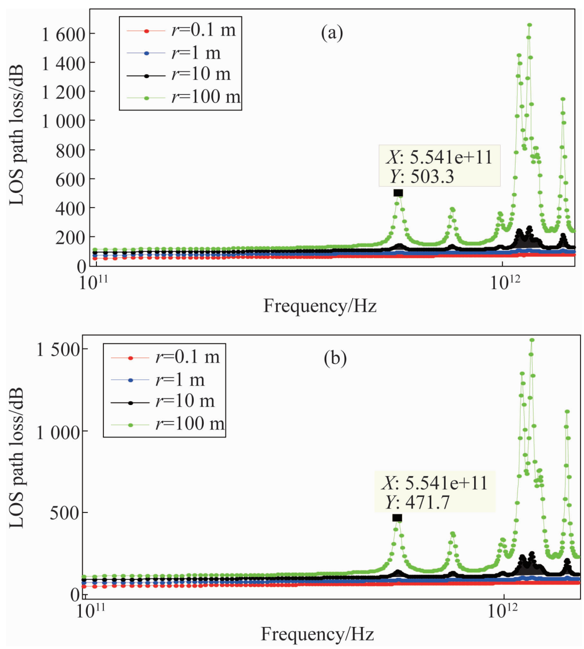

Fig. 2 (a) LOS path loss for 20℃, and (b) LOS path loss for 30℃

The transfer function of the LOS propagation path is given by,

$$H^{LOS}(f,r) = H_{spread}(f,r)H_{abs}(f,r) \quad ,(4)$$

where, $H_{spread}(f,r)=c/4\pi fr$ and

$$H_{abs}(f,r) = e^{-\frac{1}{2}\alpha_{mol}(f,T_k,p)r}$$

Non Line of Sight (NLOS) path in THz system plays a major role in enabling communication in the scenario where the LOS path is blocked by obstacles like walls and furniture. Path loss in NLOS path depends mainly on the reflection of the electromagnetic waves. Hence, it is necessary to analyze the reflection properties of the surface which depends on the building material such as roughness of the surface σ_{hs}, and correlation length l_{corr} [11]. The scattering of the EM waves at rough surfaces is employed by means of Kirchhoff scattering theory[12].

The scattering behavior of rough surface is shown in Fig. 3[9].

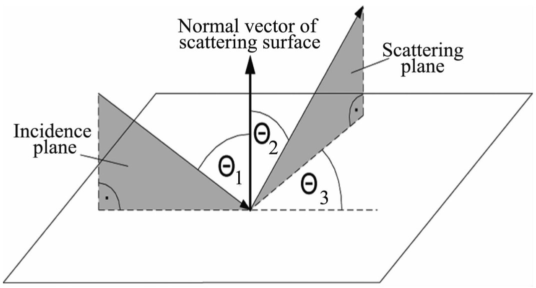

Fig. 3 Basic geometry of scattering at a rough surface

Scattering coefficient ρ determines the nature of reflected wave[9] and is given by,

$$\rho = \frac{E_{sc}}{E_{ref}} \quad ,(5)$$

where, E_{sc} is the scattered electric field and E_{ref} is the reflected electric field in the direction of specular reflection by a smooth conducting surface. In specular reflection, the incident angle and the reflected angle θ_2 are equal and hence scattering angle θ_3, in direction outside the plane of incidence equals to zero[9].

For an infinitely conductive surface of area A with dimension X and Y, the mean value of the scattering coefficient with incident angle θ_1 and the scattered angles θ_2, θ_3 is derived as,

$$E\{\rho\rho*\}_\infty = e^{-g}\rho_0^2 + \frac{\pi l_{corr}^2 F^2}{A}\sum_{m=1}^{\infty}\frac{g^m}{mm!}e^{-v_{xy}^2}l_{corr}2/(vm) \quad ,(6)$$

where,

$$g = \sigma_{hs}^2(2\pi f/c)^2(\cos\theta_1 + \cos\theta_2)^2$$
$$\rho_0 = \mathrm{sinc}(v_x X).\,\mathrm{sinc}(v_y Y)$$
$$v_x = (2\pi f/c)(\sin\theta_1 - \sin\theta_2\sin\theta_3)$$
$$v_y = (2\pi f/c)(-\sin\theta_2\sin\theta_3)$$
$$v_{xy} = \sqrt{v_x^2 + v_y^2}$$
$$F = \frac{1 + \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2\sin\theta_3}{\cos\theta_1(\cos\theta_1 + \cos\theta_2)}$$

Equation 6 is applicable for perfect conducting surface. Furthermore, the average scattering coefficient for finite conducting surface is computed by average the Fresnel reflection coefficient with scattering coefficient of the infinite conducting surface[11-12].

$$E\{\rho\rho*\}_{finite} = E\{\rho\rho*\}_\infty E\{\gamma\gamma^*\} \quad .(7)$$

For the finite conducting surface, the Fresnel reflection coefficient for the air and the material interface is computed by,

$$\gamma = \frac{1 - \eta_{eff}}{1 + \eta_{eff}} \quad .(8)$$

By considering all the derived equations, the scattered power with respect to the distance r_0 is given by,

$$E\{R_{power}\} = \left(\frac{fA\cos\theta_1}{cr_0}\right)^2 E\{\rho\rho*\}_{finite} \quad .(9)$$

The transfer function of the i^{th} NLOS path is,

$$H_i^{NLOS}(f,r,\xi_i) = H_{ref,i}(f,r_{i2},\theta_{i1},\theta_{i2},\theta_{i3}) \times H_{spread,i}(f,r_{i1},r_{i2}).\,\mathrm{Habs},i(f,r_{i1},r_{i2}) \quad ,(10)$$

where,

$$H_{ref,i}(f,r_{i2},\theta_{i1},\theta_{i2},\theta_{i3}) = \sqrt{E\{R_{power,i}(f,r_{i2},\theta_{i1},\theta_{i2},\theta_{i3})\}},$$
$$H_{spread,i}(f,r) = \frac{c}{4\pi f(r_{i1} + r_{i2})}$$
$$H_{abs,i}(f,r_{i1},r_{i2}) = e^{-\frac{1}{2}\alpha_{mol}(f,T_k,p)(r_{i1}+r_{i2})}$$

where r is the distance between the transmitter and receiver, r_{i1} is the distance between the transmitter and i^{th} the scattering point, r_{i2} is the distance between the i^{th} scattering point and the receiver.

The overall channel transfer function considering both LOS and NLOS paths is given by

$$\mathrm{HEQ}(f,r,\zeta) = H^{LOS}(f,r)e^{-j2\pi f\tau_{LOS}} + \sum_{i=1}^{N} H_i^{NLOS}(f,\zeta_i)e^{-j2\pi f\tau_{NLOSi}} \quad .(11)$$

The vector $\zeta = [\zeta_1, \zeta_2, \cdots \zeta_N]$ is coordinates of all the scattering points, which accounts for the parameters $[r_{i1}, r_{i2}, \theta_{i1}, \theta_{i2}, \theta_{i3}]$. N is the total number of NLOS paths.

In this paper, a rectangular room of (length, width, height) = (5 m, 2.75 m, 2.5 m) with four NLOS paths is considered for simulation and is shown in Fig. 4. The simulated LOS channel transfer function, NLOS channel transfer function and the complete transfer functions for a distance of 2m at 30℃ are given in Fig. 5. From the result it is clear that in the presence of LOS path it dominates the NLOS path and the complete transfer function can be approximated as LOS path transfer function.

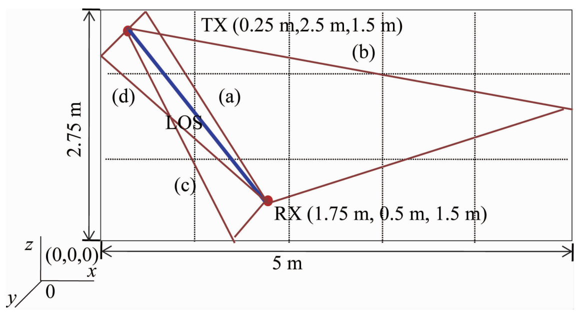

Fig. 4 Indoor scenario

2 Performance with BPSK modulation

The performance of the THz channel is evaluated with BPSK modulation scheme. BPSK is a digital modulation technique in which each bit is encoded with a phase shift over a predetermined period. Figure 6 shows

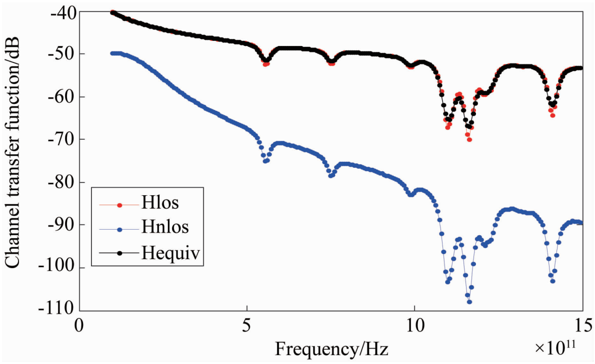

Fig. 5 Channel transfer function

the BER performance of the THz channel with BPSK modulation for different lengths. Frequency band of 0.1 to 1.2 THz has been considered for simulation.

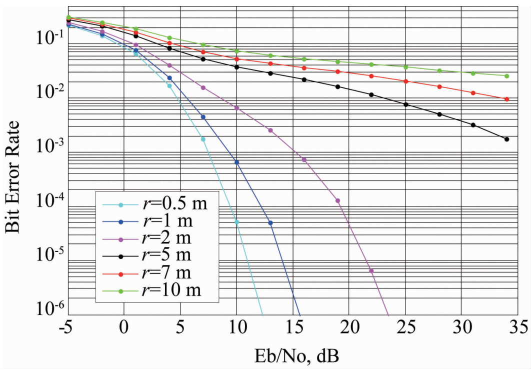

Fig. 6 The BER performance of THZ channel with BPSK modulation scheme

Performance of the channel is good for the distance of 0.5, 1 and 2 meters. As the distance increases, due to the high absorption coefficient the signal gets attenuated. Even with good SNR the noise floor dominates the signal and the performance is poor. To combat the BER multiple antennas can be used[16].

3 Performance with multiple antennas

The space dimension is exploited in Multi-Input Multi-Output (MIMO) technique. Performance of the system can be improved by employing multiple co-located antennas at the transmitter or/and at the receiver. This spatial diversity schemes enhance reliability by minimizing the channel fluctuations due to fading. The central idea in diversity is that different antennas receive different versions of the same signal. The chances of all these copies being in deep fading are small[16].

Receiver diversity is a form of space diversity, where there are multiple antennas at the receiver as shown in Fig. 7.

The received signal in the i^{th} received antenna is given by

$$y_i = h_i x + n_i \quad . (12)$$

In matrix form,

$$Y = HX + N \quad , (13)$$

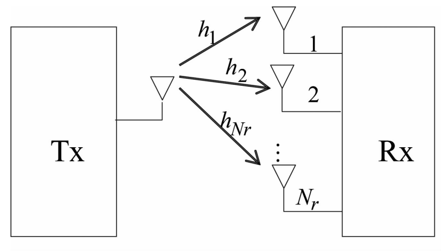

Fig. 7 Schematic of receiver diversity

where

$Y = [y_1\ y_2 \cdots y_{Nr}]^T$ is the received signal from all the received antenna, $H = [h_1\ h_2 \cdots h_{Nr}]^T$ is the channel for the antennas, $N = [n_1\ n_2 \cdots n_{Nr}]^T$ is the noise on the received signal.

Different combining techniques are used to effectively demodulate the data using the information from all antennas. In this paper, Maximum Ratio Combining (MRC) is used to estimate the data as this is optimal in terms of SNR[19]. The estimated symbol is obtained by,

$$\hat{x} = \frac{H^H Y}{H^H H} \quad . (14)$$

BER performance of the THz channel for different number of received antennas for distances 5 m and 10 m is shown in the Fig. 8. For 5 m distance there is a 7 dB gain with 32 antennas compared with 2 antennas system. For 10m distance there is no significant improvement with the increase in number of antennas.

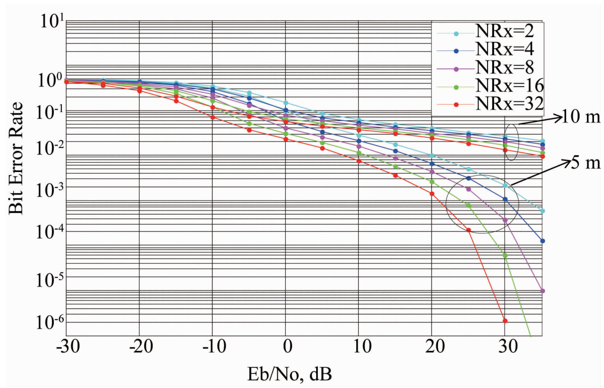

Fig. 8 BER performance of THZ channel with receiver diversity technique

4 Adaptive modulation scheme

In adaptive modulation scheme, the characteristic and limitation of the channel is taken into account for improving the performance of the system. Frequency selective abortion of water molecules in the air results in attenuation bands. The width of these high attenuation bands mainly depends on the distance and humidity in the air. In adaptive modulation these bands are excluded from data transmission. Adaptive modulation decreases the rate of transmission but it enhances the BER performance[14]. Performance of the system with adaptive modulation scheme is shown in Fig. 9. Frequency bands of 0.5 ~ 0.6 THz, 0.7 ~ 0.78, 0.93 ~ 0.98 and 1.09 ~ 1.2 are not considered for data transmission. There is a considerable improvement in the performance of the system with adaptive modulation compared with non-adaptive modulation.

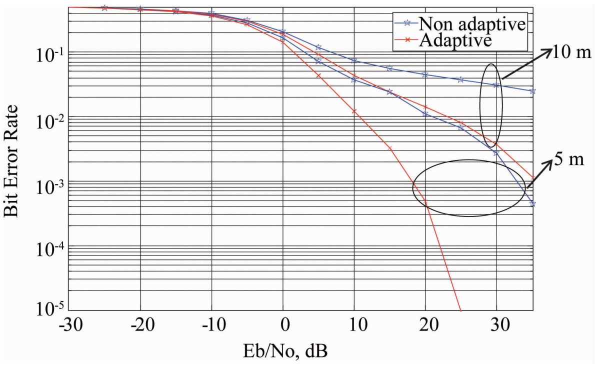

Fig. 9 BER performance with adaptive modulation

Adaptive modulation with receiver diversity has been analyzed for varying number of receiver antennas. Figure 10 shows the BER of adaptive modulation in combination with receiver diversity. For a distance of 10 m and NRx = 32, there is a 25 dB gain with and without adaptive modulation.

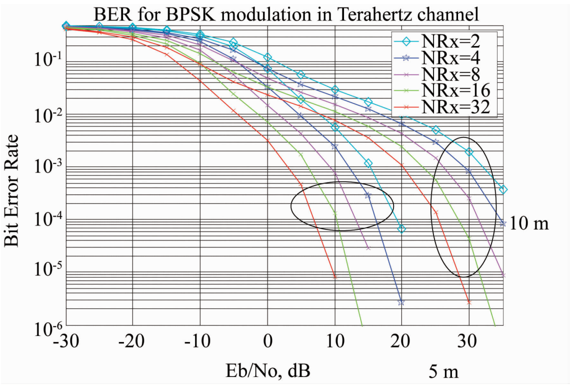

Fig. 10 BER performance with adaptive modulation and receiver diversity

5 Conclusion

THz band is intended to satisfy the demand for high data rate over wireless channel. This paper, gives an overview of channel model for THz frequency. The performance of the channel is analyzed with BPSK modulation technique. The poor BER performance of the channel is improved with receiver diversity techniques. The improvement in performance is found to be insignificant even with increase in the number of antennas because attenuation of signal in a few frequency bands are very high and noise power dominates the signal power in these bands. This can be taken care by exploring the characteristics and limitations of the channel. Adaptive modulation technique is implemented in which data is loaded only in less attenuation bands. Adaptive modulation with receiver diversity is analyzed for distance greater than 5m. A considerable improvement in the BER performance of the system is observed for the length up to 10m.

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