Statistical Characterization and Analysis of Low-THz Communication Channel for 5G Internet of Things

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Abstract

This paper presents measurements and statistical characterization to compare three potential bands of the low-THz channel, namely, the 300 to 319 GHz, 340 to 359 GHz and 380 to 399 GHz bands. From the large set of measurements performed in line-of-sight (LoS) and non-LoS (NLoS) environments, parameters for path loss model with shadowing are evaluated. Our results show that the path loss exponents for the band around 310 GHz, 350 GHz, and 390 GHz is 2.07, 1.90 and 1.96, respectively. The impacts of different materials acting as surfaces in LoS channels and reflectors in NLoS environments are also examined. Additionally, the statistical analysis due to temporal, spatial and multipath propagation is performed to determine the best fit distributions. Finally, we look at some networking scenarios in THz Band communication to derive the expressions for the number of connections a user can make based on antenna characteristics, data rate requirements and antenna mobility as well as network density. Our results suggest fundamental parameters that can be used in future THz Band analysis with applications in both macro and micro scale Internet of Things (IoT).

Keywords: 5G wireless networks; channel modeling; statistical characterization; Terahertz (THz) channels; THz propagation.

1. Introduction

The inter-networking of devices, buildings, vehicles and other items such as wearable electronics that comprise technologies labeled under the banner of Internet of things (IoT), are quickly molding the future of technology in the current era. Furthermore, the demands for higher data rates for communication are in high demand to cater for soaring data consumption for new applications such as high-resolution videos and 3D experience environments. In order for the technology to compete with consumer needs, 5G wireless networks need to realize data rates reaching terabits per second (Tbps) and support higher connection density [1, 2, 3, 4, 5, 6, 7, 8]. The 60 GHz spectrum is expected to increase data rates up to 6 Gbits/s [9, 10] but the available spectrum around this frequency is limited to 9 GHz that may not completely satisfy the increasing demands of higher data rates. To support such high throughputs of Tbps and higher connection density, enormous bandwidth is required along with higher area spectral efficiency, and hence, researchers around the world are exploring the Terahertz (THz) Band (0.3 - 10 THz) [11, 12, 13, 14, 15, 16].

Higher frequencies can support higher data rates, however, being highly directional, they are more easily blocked by any obstacles on their path providing a set of unique challenges for THz Band communications. However, this characteristic of THz Band inherently provides higher connection density. THz Band equipment is constantly improving performance with current research activities. The experimental THz Band equipment can be categorized mainly into two groups depending on the approach for generating THz Band signals. In a top-down approach, photonics technology is used to achieve communication that is down-converted from optical to lower frequency electronic signals, while in a bottom-up approach, the operating frequency of electronics components is increased [17]. The bottom-up approach is a preferred course for consumer designs because optical components are more expensive than silicon components used in the bottom-up approach, thus reducing the component costs [18]. The sizes for silicon-based components are also more compact. The commonly used

THz Band experimental setups are based on bottom-up approach involving sub-harmonic Schottky diode mixers [19, 20, 21].

The first step in designing any cellular network for a particular frequency band is to understand its channel characteristics and material behavior [22, 23, 24]. The channel characterization is followed by development of accurate channel models. A detailed analysis of the entire band wavelength range (1 - 0.75 mm) in various indoor environments with several common indoor scenarios will help to characterize the channels for THz Band and give important information for the networks working in such environment.

In this work, we first installed a Vector Network Analyzer (VNA) and subharmonic mixer based THz Band equipment and performed detailed experiments for channel sounding. The current generation of network analyzers available in the market support frequencies up to 70 GHz. Therefore, to characterize frequencies in THz Band, external subharmonic mixers are used. Little literature is available that provides in-depth analysis of THz Band indoor channels. Most of the previous work uses narrow band equipment and explore only 300 to 320 GHz Band [22, 23, 25, 26, 27, 28, 29, 30]. Secondly, the materials used were very limited in them.

For thorough statistical channel characterization, three bands of 19 GHz were selected from low-THz Band and a large set of experiments for line-of-sight (LoS) and non-line-of-sight (NLoS) cases were conducted. The tested bands included the ranges of 300-319 GHz, 340-359 GHz and 380-399 GHz. LoS experiments were carried by varying distances between the transmitter and receiver to record path loss in all bands. Several obstacles that are commonly encountered in an indoor channels such as transparent plastics, keys and mobile phones were used in the LoS experiments to measure the effects of shadowing. From the large set of data, path-loss exponents and variations due to shadowing were measured for all the tested bands. NLoS experiments included response measurements of reflections from various surfaces also present in indoor environments, such as ceiling panels and various metals. Additionally, experiments were performed to test various desktop table materials such as wood, metal and rubber to find the

effect of the surfaces on which the communication takes place. Based on the analysis of multipath propagation, we show unprecedented power delay profile, root mean square (RMS) delay spread, mean excess delay and maximum excess delay with picoseconds accuracy and coherence bandwidth for LoS and NLoS environments for the all the bands under consideration.

The goal of this research is threefold;

- extensive measurement campaign to understand channel characteristics with different materials and environments expected in a THz Band wireless channel used for IoT;
- full analysis of three potential bands of 300 to 400 GHz channel with in-depth comparison integrated in single article;
- determine the potential of network performance and density of a THz Band wireless channel.

The signal characteristics found by the analysis are not limited to macroscale networks, they can also be applied to similar microscale scenarios. The remainder of this paper is organized as follows. In Section 2, we describe our measurement system used for experimentation along with its characterization. Statistical characterization of the low-THz Band is provided in Section 3. Section 4 provides the small-scale multipath propagation analysis. Networking in THz Band is discussed in Section 5. Finally, we conclude the paper in Section 6.

2. The Measurement Equipment and Site

The THz Band indoor channel measurements were conducted with a custom configured wideband frequency domain channel sounder. The equipment was installed in a typical office environment to measure indoor channel propagation characteristics. Experimentation in THz Band is rather difficult due extremely small wavelength (1 - 0.1 mm) and the fact that single solution testbeds are not yet available, therefore, modifications are required to the contemporary

Figure 1: Block diagram of THz Band measurement setup.

equipment. In this section, we describe our testbed used for the experimentation and provide details of the experiment site.

2.1. Testbed Specifications

The measurement setup can be categorized into two main parts, Anritsu VNA MS4647B and VDi WR2.8MixAMC extension modules. The VNA MS4647B measures channel impulse response in frequency domain. However, the upper limit of this device is 70 GHz and to measure the channel impulse response at 300 GHz and above, WR2.8MixAMC extension modules are attached to the VNA. These modules contain subharmonic mixers that upconvert the VNA test signal and transmit it to the channel. This signal is received at the receiver and fed back to the VNA after downconversion. The VNA monitors changes in the amplitude and phase of the transmitted and received signals to show the scattering parameters (s-parameters).

The extension module, VDi WR2.8MixAMC operates from 260 GHz to 400 GHz with a typical Single-Sideband (SSB) mixing loss of 15 dB. The test port waveguide has a cutoff frequency of 211 GHz. A pair of these modules is attached externally to the VNA to measure THz Band channel [20]. The maximum

Figure 2: Measurement equipment losses.

Figure 3: Measurement equipment losses after calibration.

bandwidth supported by the module is 20 GHz, however, the coupler used for upconversion limits it to 19 GHz as its operating range is from 1 GHz to 20 GHz. Hence, all our measurements are for 19 GHz wide bands. The block diagram of our setup is shown in Fig. 1. The local oscillator signal f_{LO} , required by extension module, is provided using a Yttrium Iron Garnet (YIG) based tunable synthesizer. The frequency of f_{LO} is selected based on the frequency band required at the antenna. For instance, to generate $\{300, 340, 380\}$ GHz

Figure 4: Antenna gain 260 GHz to 400 GHz range.

signal, we set $f_{LO} = \{12.45833, 14.12500, 15.79166\}$ GHz, respectively which is then multiplied by a factor of 24 to be fed to the f_{LOTHz} port of subharmonic mixer. Intermediate frequency f_{IF} port of the mixer is swept by the VNA from 1 to 20 GHz to generate $(f_{LOTHz} + f_{IF})$ at the output. Phase coherence in our setup is achieved by using a common local oscillator that provides synchronized frequency signals to all the components. However, the subharmonic mixer used produces Double Sideband (DSB) and thus using a common f_{LO} at both the transmitter and the receiver causes two frequencies to accumulate after homodyne down conversion. To avoid this behavior, a small offset should be added between the f_{LO} of the transmitter and the receiver so that the unwanted frequency may be easily filtered out [31].

2.2. Testbed Configuration

The full 19 GHz channel impulse response at $\{300, 340, 380\}$ GHz was measured by recording s-parameters S_{21} for the $f_{IF} = 1$ to 20 GHz. The transmitter f_{IF} input power was set as -10 dBm (0.1 mW). The relatively low input power was necessary in order to avoid damaging the transmitting subharmonic mixer, as well as the receiving subharmonic mixer at short link distances. Additionally, the low output power of -10 dBm EIRP (considering

10 dB coupler loss, 15 dB mixing loss and 25 dB antenna gain) emulated office desktop channel where it is required to keep a transmitted signal within the boundaries of a table. The transfer function of the transceiver is shown in Fig. 2, which is obtained by directly interconnecting the transmitter and the receiver. It is evident from the transfer function that these losses should be excluded while measuring the channel impulse response. Calibrating the VNA can exclude these losses along with other defects in measurements. Several types of calibrations can be performed depending on the application of interest [32, 22, 33, 34]. In our case, through/reciprocal calibration is performed to correct the amplitude of the measured channel impulse response. This was achieved by directly connecting the transmitter's waveguide with the receiver's waveguide [35]. The transceiver response after calibration is shown in Fig. 3.

To compensate the significant path loss at THz frequency, high gain diagonal horn antennas are used at the transmitter and the receiver. Gain of the antennas at center frequency is 25 dBi each. Whereas at the lowest frequency (260 GHz) it is 2 dB lesser and at the highest frequency (400 GHz) it is 1.5 dB higher. The half power beamwidth is 12° . The gain of our antenna, from 260 to 400 GHz, is shown in Fig. 4. For all the three bands, transmitter and receiver antennas are vertically polarized. In the later sections of this paper, since all measurements are performed while an antenna is attached at each end, the antennas will be considered a part of the transfer function.

S-parameters for the 19 GHz bands were recorded with 2 MHz of frequency step, 10 points averaging and 1 KHz IFBW. These parameters significantly reduce noise floor and improve dynamic range [32, 36] to provide spatial and temporal resolutions of 0.1578 mm and 0.526 ps, respectively. The average noise floor of the VNA is -103.4374 dB (Fig. 2), however, for our calibrated system, the average noise floor is -59.4123 dB (Fig. 3), which is also the dynamic range of our testbed. The number of sweep points is set to 9501 and the maximum excess delay is 4 ns. A summary of measurement parameters is given in Table 1.

Table 1: Setup parameters.

Parameter	Symbol	Value
<i>Measurement points</i>	N	9501
<i>Test signal power</i>	P_{in}	-10 dBm
<i>Start frequency</i>	f_{start}	1 GHz
<i>Stop frequency</i>	f_{stop}	20 GHz
<i>Bandwidth</i>	B.W.	19 GHz
<i>IFBW</i>	Δf_{IF}	1 KHz
<i>Average noise floor</i>	P_N	-103.4 dB
<i>Dynamic range</i>	R_{DYN}	60 dB
<i>Time domain resolution</i>	Δt	0.5 ps
<i>maximum excess delay</i>	τ_m	4 ns

2.3. Site Description

Our experiments were performed in NWCL lab, which is a typical indoor office environment. On a typical office desktop, the LoS communication is operated at distances between 5 and 70 cm. Our experimental setup as shown in Fig. 5(a) was used for LoS measurements and the scheme for measurements at different transmitter-receiver separations is shown in Fig. 5(b). Several measurements were taken at each transmitter-receiver separation on different time instances to capture temporal variations for each of the frequency bands and then the transmitter-receiver pair was moved further apart to a new position. An average measurement, involving the mean of 10 previous temporal reading was also generated. A similar mechanism was adopted to characterize various desktop table materials to check the effects of table materials on THz Band communication. It should be kept in mind that at such small distances, molecular absorption is negligible and therefore was not observed in our experiments [16].

To create shadowing in the channels, different objects were placed between the transmitter and receiver, and again several temporal instantaneous and

(a)

(b)

(c)

(d)

(e)

(f)

Figure 5: (a), (b) Measurement setup for LoS experiments with linear displacement. (c), (d) Measurement setup for spatial displacement. (e), (f) Measurement setup for NLoS experiments with a reflective surface.

average readings were recorded. The setup of shadowing by means of plexiglass is shown in Fig. 5(a). The LoS measurement setup and scheme for spatial displacement is shown in Fig. 5(c) and (d), respectively. Keeping the distance

between the transmitter and receiver fixed at 10 cm, the setup was spatially displaced, each time with a difference of 30° from the previous position. Thus, the spatial data from 12 different locations was collected for the spatial LoS measurements.

Finally, for the NLoS reflections, the transmitter and receiver were placed perpendicular to each other and a reflection surface at 45° was placed between the two as shown in Fig. 5(e) and (f). Different reflective surfaces that are common in an indoor office environment such as ceiling panels, paint-coated aluminum surfaces of typical office cabinets and copper were used. Fig. 5(e) shows a measurement in progress using a ceiling panel as a reflection surface.

3. Statistical Characteristics of Low-THz Band Channel

Channel modeling is one of the most difficult parts of wireless communications as its prediction requires detailed knowledge of the environment. Usually, site description is not easily available and thus statistical models can be very helpful in predicting the channel behavior. It should be noted that the statistical characteristics of the measured channel depend on the antenna radiation pattern and the location. In this section, we statistically determine a large-scale propagation model for an indoor desktop table.

200 3.1. Path loss model and shadowing

To determine the path loss model for a desktop channel, we have measured s-parameters of the channel with antennas attached at the transmitter and receiver for different distances. The path loss at a particular distance can be referred as,

$$PL = \frac{P_t}{P_r} = -S_{21}. \quad (1)$$

where P_t and P_r are transmit and received power, respectively and S_{21} are the s-parameters. The local mean path loss is obtained by averaging measured

Figure 6: Uncalibrated measured and theoretical path losses with transceiver response included.

Figure 7: Measured and theoretical path losses after calibration of VNA.

impulse response over time and frequencies, i.e.,

$$\overline{PL}(d) = \frac{1}{MN} \sum_{i=1}^N \sum_{j=1}^M |H(f_i, t_j, d)|^2, \quad (2)$$

where, $H(f_i, t_j, d)$ is the measured impulse response of the channel, N is the number of observed frequencies, M is the number of times impulse response is measured and d is the distance in meters.

LoS channels make the case for simplest channel model and a sample measurement setup is shown in Fig. 5 (a). In these experiment, we measured path loss at different distances ranging from 10 cm to 75 cm, that are often expected in a typical office desktop table or a TV stand. All the measurements were performed on a wooden base and the antenna height in the system was kept at 7 cm. The number of frequency-response snapshots over time was $M = 10$ which was observed to be adequate for temporal analysis.

To appreciate the importance of calibration in our setup, we have shown s-parameters of different distances at frequencies ranging from 340 to 359 GHz for the case when the transceiver was not calibrated, in Fig. 6. We can observe that the path loss increases with frequency and does not follow the theoretical path loss. The reason for this apparent aberration is the frequency-dependent response of the transceiver shown previously in Fig. 2. Note that the response includes antennas with a gain of 25 dBi and is hence considered as a part of system. Therefore, while considering channel transfer function, the gain of antennas may be subtracted using Fig. 4. After the calibration was performed, the results were fairly improved and a better match between the measured and theoretical path loss was observed, as shown in Fig. 7. However, the path loss variations across the frequency indicate that extensive equalization would be required for such a wide band system. Moreover, increased loss at higher distance was observed and can be attributed to the higher system noise floor.

The path loss for different distances on desktop tables with different surface materials was measured at different times and mean path loss was calculated and shown in Fig. 8 for 300-319 GHz band measurements. It can be observed in Fig. 8 that the temporal variations over time are minimal. Similar results were observed for 340-359 GHz band and 380-399 GHz band. The first 10 measurements are temporal measurements in which the antenna was kept 7 cm above the table. While measurement 11, 12 and 13 correspond to measurements taken with antenna height of 1 cm above wood, aluminum and rubber surface respectively. Since the channel is static, there is no additional clutter added over time that would cause any significant variation. This concludes to the fact

Figure 8: Path loss versus transmitter receiver separation in LoS environment for 300-319 GHz.

Figure 9: Path loss versus transmitter receiver separation in LoS environment for 340-359 GHz.

that 10 measurements are fairly sufficient to capture all temporal variations in a THz Band desktop channel.

For a more extensive path loss model, we observed the effects of shadowing in our channel by rotating our transmitter and receiver on several spatial positions as well as placement on the desktop tables with surfaces of wood, aluminum and

Figure 10: Path loss versus transmitter receiver separation in LoS environment for 380-399 GHz.

Table 2: Path loss for different desktop surfaces.

Freq (GHz)	Free Space(dB)	Wooden (dB)	Aluminium(dB)	Rubber(dB)
300-319	15.3754	13.2688	14.28	13.3464
340-359	12.4336	10.8362	11.8505	11.4571
380-399	11.4274	9.7417	10.7517	10.4883

rubber by placing them 3 cm above the antennas, to observe spatial variation. It was observed that, path loss on a wooden table was slightly less than the rubber followed by an aluminum table. The average values are summarized in Table 2. Furthermore, a comparison with existing work is shown in Table 4. Moreover, we placed different objects such as plexi glass, metal keys, mobile phone and human hand to observe the affect of all these obstructions. The cumulative distribution functions (CDF) of all the shadowing objects in 300-319 GHz, 340-359 GHz and 380-399 GHz band are shown in Fig. 11(a), Fig. 11(b) and Fig. 11(c), respectively. It can be observed that the shadowing follows normal distribution. For the CDFs, it was concluded that only optically transparent objects would allow the THz Band signal to pass through them and thus the opaque objects were not included in the shadowing variable. For an observed

Table 3: Values of measured path loss exponent n and σ for low-THz Bands.

Freq (GHz)	n	Standard Deviation	σ (dB)	Standard Deviation(dB)
300-319	2.0341	4.417	0.9540	0.9767
340-359	1.9040	0.1229	2.548	1.59
380-399	1.9531	4.0732	1.2198	1.1044

Table 4: Pathloss exponent values from various measurement campaigns.

Ref	Scenario	Carrier	PLE	σ
[37]	Indoor; LoS on desktop	285-320 GHz	1.892	-
[22]	Indoor; LoS on desktop	300 GHz	2.17	-
[23]	Indoor; LoS on desktop	300 GHz	1.927	0.67

channel, path loss over a particular distance can be modeled by the path loss exponent model with log-normal shadowing as [38, 39, 40, 41, 24]

$$\overline{PL}(d) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma, \quad (3)$$

where, $\overline{PL}(d)$ is the average path loss in decibels at the distance d , n is the path loss exponent which indicates the rate at which the path loss increases with d , $PL(d_0)$ is the path loss at reference distance d_0 and X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB).

The values of n and σ in (3) are computed from the measured data, using least square linear regression fitting through the scatter of data such that the error between measured and estimated path loss is minimized in a mean square error sense over the numerous measurements for different transmitter-receiver distances. The model parameters were calculated for all three bands with the reference distance $d_0 = 1\text{ m}$. The free space path loss including the antenna

Figure 11: Scatter plot of shadowing showing Gaussian CDF in (a) 300-319 GHz, (b) 340-359 GHz and (c) 380-399 GHz.

gains at this distance is 33.37 dB, 32.52 dB and 31.97 dB, respectively for all these bands. The results are summarized in Table 3. The path loss exponent, n , is calculated as 2.0341, 1.9040 and 1.9531 for 300-319 GHz, 340-359 GHz and 380-399 GHz bands, respectively. The values of σ along with Fig. 11 show that the shadowing X_σ is indeed Gaussian.

3.2. Non-line-of-sight Channel Measurements

The indoor desktop communication channel that we have considered in this work is susceptible to significant losses due to the presence of shadowing [42]. Mainly shadowing is caused by any obstacle appearing between transmitter and receiver. This obstacle attenuates the signal power depending on the material type. A strong attenuation can even block the signal and stop communication. Absorption coefficient of different materials was determined using the transmission loss. The attenuated signal power was subtracted from the reference signal to get added transmission loss due to the object. Finally, this extra loss was used to calculate the absorption coefficient of the material [43]. For instance, a clear glass with thickness of $t_{glass} = 2 \text{ mm}$ or a 80 gram fiber mat with thickness of $t_{fiber} = 3 \text{ mm}$, attenuation of approximately 6.14 dB and 27.55 dB, respectively, were measured at 310 GHz. In the case of a human hand placed as obstruction, 45.6 dB of attenuation was observed. The attenuation coefficient of different materials is summarized in the Table 5.

The results show that, if a thin glass or a fiber sheet appears as obstruction

Table 5: Absorption coefficient of different objects

Object	α_{310GHz}	α_{350GHz}	α_{390GHz}
<i>Fiber mat</i>	0.169 mm^{-1}	0.171 mm^{-1}	0.173 mm^{-1}
<i>Glass</i>	0.049 mm^{-1}	0.048 mm^{-1}	0.049 mm^{-1}
<i>Empty water glass</i>	0.959	0.962	0.965
<i>Hand</i>	0.990	0.982	0.994

in the communication link, the SNR of channel decreases, and hence, the data rate also decreases. However, if obstruction is a human hand, the intense signal attenuation might lead to disconnection of communication link. To reestablish a link in such scenarios, the system should turn to NLoS paths using reflection properties of the materials present in the environment. In a typical indoor environment, objects like metallic surfaces of aluminum and copper coated with paint and ceiling panels are ubiquitous. Using these three materials as reflectors, we measured NLoS path loss with the experimental setup discussed in Fig. 5 (e) and (f). As a sample scenario, we selected the reflecting surface as equidistant from both the transmitter and the receiver at a distance of 12.3 cm. This makes the total length traversed by a reflection to be 24.6 cm. The selection of these specific distances is guided by the limitations of our experimental setup. Fig. 12 compares the measured NLoS path loss for paint-coated aluminum, copper and acoustic ceiling panel with the theoretical path loss. It can be seen that the signals reflected from these objects are strong enough to provide a NLoS in a desktop channel with the metal plates working almost equivalent to the theoretical path loss expectation. Ceiling panels do not perform as well as metals due to their rough surfaces but still the signal reflected by them is above noise level in any case.

It is important to note that if the reflective surface is moved to a different position, a corresponding change in the path loss may occur based on the new effective distance between the transmitter and the receiver as well as antenna properties such as the direction of the antenna beam width and the shape of the

Figure 12: NLoS communication with different reflective surfaces.

antenna beam, however, the general characteristics will be similar to the ones observed here.

4. Small-Scale Multipath Propagation

Multipath in a wireless channel creates small-scale fading effects that manifest as rapid changes in the signal strength. It happens when a transmitted signal reaches the receiver from different directions with different propagation delays. These waves add up vectorially at the receiver antenna and can cause severe distortion or fading. Such a channel impulse response can be characterized as [38]

$$h(t, \tau, d) = \sum_{k=1}^L a_k(t, d) \exp(j\theta_k(t, d)) \delta(t - \tau_k), \quad (4)$$

where τ_k is the excess delay of the k th multipath component relative to the first arrival, L is the number of multipath components, a_k represents the amplitude of the k th component, θ_k is its phase and $\delta(\cdot)$ is the Dirac delta function.

Using the dual relationship of time domain and frequency domain technique, the channel impulse response was calculated by taking inverse discrete Fourier transform (IDFT) of the measured frequency response. This helps in determining the time dispersive properties of a wide band multipath channel. The

Figure 13: Normalized power delay profile in LoS channel.

common parameters used to quantify the dispersive property are the mean excess delay (τ_m) and RMS delay spread (σ_τ). The mean excess delay is the first moment of the power delay profile and is defined as

$$\tau_m = \frac{\sum_{k=1}^L a_k^2 \tau_k}{\sum_{k=1}^L a_k^2}, \quad (5)$$

whereas the RMS delay spread is the second central moment of the power delay profile and is defined as

$$\sigma_\tau = \sqrt{\tau_c^2 - \tau_m^2}, \quad (6)$$

where,

$$\tau_c^2 = \frac{\sum_{k=1}^L a_k^2 \tau_k^2}{\sum_{k=1}^L a_k^2}. \quad (7)$$

These equations only rely on the amplitudes that are relative to the first detectable signal arriving at the receiver and do not rely on the absolute power level of the received signal. Thus, the impulse response is normalized to clearly observe the power delay profile and excess delay. The noise threshold level is chosen 10 dB above the system noise level which comes out to be approximately -50 dB. The mean values of τ_m and τ_{RMS} are 44.2926 ps and 231.435 ps, respectively for the 340-359 GHz band. The power delay profile for 10 cm, 15 cm, 40

Table 6: Time dispersion parameters in LoS channel.

Freq (GHz)	Distance (cm)	τ_m (ps)	σ_τ (ps)	τ_{max} (ns)	B_c (GHz)
<i>300-319</i>	10	6.88	71.48	2.50	2.79
	15	14.41	114.87	1.92	1.74
	40	58.76	375.00	2.62	0.53
	75	104.85	410.43	2.74	0.50
<i>340-359</i>	10	3.99	44.58	0.87	4.48
	15	7.02	84.62	2.92	2.36
	40	58.21	388.56	2.63	0.51
	75	107.94	407.97	2.70	0.49
<i>380-399</i>	10	18.92	92.31	0.91	2.16
	15	23.01	117.86	2.93	1.69
	40	54.18	312.03	2.63	0.64
	75	103.90	409.65	2.74	0.53

cm and 70 cm transmitter-receiver separation is shown in Fig. 13. The results show that there are multipath signals, above the threshold value, arriving after the main signal. These mulipaths reduce the coherence bandwidth (B_c) of the channel which is the bandwidth over which the channel can be considered flat. For a bandwidth above which correlation function is above 0.5, $B_c \approx 1/5\sigma_t$ [38]. The τ_m , τ_{RMS} , the maximum excess delay (τ_{max}) for -40 dB threshold and B_c for the various frequency bands are summarized in Table 6. The results show that the B_c is much less than the actual bandwidth and utilizing the full bandwidth efficiently would not be straight forward without stringent channel equalization. Furthermore, B_c decreases with the increase in the distance between the transmitter and receiver due to normal path losses.

Finally, we also analyze the temporal autocorrelation function in Fig. 14 for the frequency band of 340-359 GHz. The normalized temporal correlation function is calculated using

$$R(\tau) = \frac{E[h(t)h(t+\tau)^*]}{\sqrt{E[|h(t)|^2]E[|h(t+\tau)|^2]}}, \quad (8)$$

Figure 14: Normalized temporal correlation function in LoS channel.

where $(\cdot)^*$ denotes complex conjugate operation, and $E[\cdot]$ is expectation operator. The results in Fig. 14 show that the correlation function drops below 0.2 after 0.71 ns for all the tested distances. However, at some distances in between, the function value increase above 0.2 and the signal may get correlated again. Similar results were generated for the other two bands as well.

5. Network Performance and Density

Based on the channel characteristics we obtained in earlier sections, it is evident that devices operating in THz Band require stringent channel conditions to provide optimal performance. Thus, it can help us to determine the minimum distance required between the nodes in a network of THz Band devices. Apart from the path loss at different distances, the inter-device distance in a THz network must be such that the interference remains minimum. The interference between two neighboring nodes is highly dependent on the radiation patterns of the antennas they use.

To analyze a THz Band network, we first consider a simple network where several receivers are placed at a fixed diameter from a base station and consider the effects of shadowing and NLoS communication to be negligible. In order

to achieve LoS communications between one transmitter and multiple receivers, it is assumed that the transmitter antenna can be displaced angularly within an angular range known as antenna movement freedom (AMF). Thus, keeping the distance same, a transmitter can connect to various receivers. To maximize the number of receiving devices in a coverage area, the angle between two neighboring receivers intuitively should at least be equal to half-power beam width (HPBW) angle of the transmitter antenna. However, the two receivers will still cause interference for each other necessitating some further separation. This step is necessary to keep the signal to noise ratio (SNR) and the corresponding data rate in check according to the quality of service (QoS) decided by the network. We denote this additional separation as guard width (GW). The described scenario is shown in Fig. 15.

Considering a transmitter-receiver distance of 10 cm, the SNR is 47.72 dB in 340-359 GHz band. The corresponding values of SNR in 300-319 GHz and 380-399 GHz bands are 44.91 dB and 47.99 dB, respectively. The HPBW of our antennas is 12° , which gives the minimum distance between the receiver devices without any GW to be at least 20.9 mm at 10 cm distance from the base station. The interference signal at 6° farther is 6 dB below the main signal, this is elaborated in Fig. 16 which is calculated using the antenna radiation pattern of our system. It can be seen that by increasing the GW, the interference level decreases significantly.

To determine the optimum GW value such that the communication can be conducted at a particular data rate, we calculate the capacity of the channel for each GW angle value using Shannon's capacity theorem,

$$C = B_c \log_2 \left(1 + \frac{P_r}{I + N} \right), \quad (9)$$

where P_r is the received signal power, I is the interference signal and N is the noise power. Using the coherence bandwidth ($B_c = 4.48$ GHz), noise power and interference power measured previously for 340-359 GHz band, we calculate the channel capacity at each GW. This determines the optimum GW to be 14° for our system as shown in Fig. 17. Therefore, to maximize the data

Figure 15: A THz Band network with a single base station transmitter and several receivers.

Figure 16: Interference level related to the received signal strength and GW.

rates in the network, a GW of 14° is required in addition to the HPBW. Therefore, for optimum data rate between neighboring receivers a separation of 24° ($HPBW/2 + GW + HPBW/2$) with respect to the transmitter is required. On the other hand, more receivers can be present in the system if a lower data rate is acceptable. Our current system allows 3 devices to be kept within a 90° AMF for maximum data rate constraint and data rates would reduce if more devices are placed. Fig. 17 shows the relationship between GW and data rate where we see that once the receiver separation is greater than GW, maximum data

Figure 17: Data rates with respect to GW in 340-359 GHz band.

rates are achieved. Rates less than the maximum are also achievable in the case that some users have a lower QoS demand. In such cases, more devices may be connected to the transmitter in a certain area. For any general THz system, the number of devices a transmitter can connect to for a given AMF can be calculated as

$$N = \frac{AMF}{HPBW + GW}. \quad (10)$$

Let us now consider a scenario where THz Band devices are in the form of an adhoc network. Considering a set of mobile devices working on different data rates, the network shape will be changing randomly. In such a network, the overall network density at a certain time is a function of how individual nodes connect to their neighboring nodes. Network density (ND) of such a network can be calculated as

$$ND = \frac{\sum_{i=1}^N \sum_{j=1}^N E(i, j)}{2PC}, \quad (11)$$

where $PC = N * (N - 1)/2$ is the total number of potential connections that may exist in the network having N nodes and $E(i, j)$ is a function that decides if a valid edge exists between two nodes or not. $E(i, j) = 0$ if the LoS clearance between nodes is less than $HPBW + GW_R$ for a data rate R when node i is transmitting data to node j or the distance between the two nodes is greater

than the maximum coverage area of node i or for the special case when $i = j$. In all other cases, the network has a valid actual connection.

In a real life scenario, with several types of severe shadowing, the THz Band becomes very susceptible to link outages in a dense indoor environment. In such cases, adding diversity at nodes in terms of multiple-input-multiple-output (MIMO) antennas may help provide higher data rates and secure communications [44].

6. Conclusion

In this paper, we have provided and compared the statistical characteristics of several low-Terahertz Band channels, namely, the 300 to 319 GHz band, 340 to 259 GHz band and 380 to 399 GHz band. The experiments were carried using a Vector Network Analyzer and subharmonic mixers based channel sounder. Testbed specifications, configurations and site descriptions are discussed in detail. Around 600 different measurements were recorded with spatial and temporal variations, that included LoS and NLoS environments, for all the three potential bands. The large-scale path loss models for all the three bands were evaluated using the single slope path loss model with shadowing. Our work shows that the models are quite comparable as the path loss exponent for 310 GHz band, 350 GHz band and 390 GHz band is 2.07, 1.90 and 1.96, respectively, while the variations due to shadowing were confirmed to be normally distributed, for all the three bands. Moreover, NLoS measurements were performed by using the optically opaque objects as reflectors to measure the path loss. It was observed that metals, wood and even acoustic ceiling panel can be used as a reflector in THz Band channel.

Furthermore, small-scale multipath propagation was also statistically analyzed in an indoor environment. The channel impulse response was calculated by taking IDFT of the measured frequency response. It was observed that strong multipath components were present in LoS and NLoS environments. To describe the multi path properties of the channel, we have calculated mean ex-

cess delay, RMS delay spread and the coherence bandwidth. The results show that the high RMS delay reduces the coherence bandwidth a lot, making it necessary to use equalizers in THz Band communications. This finding suggests that efficient equalizer should be designed in order to fully benefit from the wide available bandwidth of THz Band channel. Finally, we have also calculated the autocorrelation function of the channel impulses response and it was observed that at times the channel might show correlation higher than 0.2.

By applying virtual antenna array technique on the similar equipment, first results of a Terahertz (THz) Band line-of-sight (LOS) 2×2 multiple-input multiple-output (MIMO) channel were presented in [45]. This progress shows the potential of THz Band and further encourage its usage in 5G indoor IoT.

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