Ultra-Wideband Terahertz Channel Propagation Measurements from 500 to 750 GHz

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Abstract—This paper presents empirically based ultra-wideband and directional channel measurements, performed in the Terahertz (THz) frequency range over 250 GHz bandwidth from 500 GHz to 750 GHz. Measurement setup calibration technique is presented for free-space measurements taken at Line-of-Sight (LoS) between the transmitter (Tx) and receiver (Rx) in an indoor environment. The atmospheric effects on signal propagation in terms of molecular absorption by oxygen and water molecules are calculated and normalized. Channel impulse responses (CIRs) are acquired for the LoS scenario for different antenna separation distances. From the CIRs the Power Delay Profile (PDP) is presented where multiple delay taps can be observed caused due to group delay products and reflections from the measurement bench.

Index Terms—Directional channel, Propagation, Power Delay Profile, Specific attenuation, Terahertz.

I. INTRODUCTION

As the rise in data traffic is growing exponentially, data rates in excess of 10 Gigabit-per-second (Gbps) may be expected in a few years from now [1]. This extraordinary need for higher data rates has led the research community in exploring parts of the EM (Electromagnetic) spectrum that can allow future expectations to be met. The THz band (0.1-10) has been identified as a candidate for major advances in the fields of wireless mobile communications such as high-speed Local Area Networks (LANs), nano-machine communications in nano-networks, chip-to-chip connectivity and security [2]-[5]. It holds several advantages such as high-speed data transmission, negligible latencies and terabit-per-second (Tbps) throughput. The lower end of the THz spectrum (0.1-1 THz) has recently been in the center of attention for realizing various applications related to 5G communications and beyond while this part of the spectrum is mostly unoccupied with frequency bands being allocated up to 300 GHz by the Federal Communications Commission (FCC)[6]. Frequencies higher than 300 GHz in the lower end of the THz spectrum are ideal for THz spectroscopy as different material show high absorption characteristics at specific frequencies due to the high frequency selectivity of the THz channel. Emerging applications in the field of THz spectroscopy include imaging, remote sensing and material characterization [7], [8].

For the development of efficient communications systems operating in the THz band, it is important to describe the characteristics of the channel the wave will propagate through. Studies conducted for channel characterization have so far been limited to the lower end of the THz spectrum as the technology has not yet developed sufficiently for generation and detection of waves at such high frequencies. Generation of THz signal cannot happen using conventional methods in electronics such as THz time domain spectroscopy (TDS) and Vector Network Analyzers (VNAs) without suitable up conversion since the signal requires very fast alternating currents. Similarly, optical systems like the ones used in infrared would require their wavelength to be similar in dimension to the wavelength of the THz wave. This would be very hard to achieve due to electron jumps between energy levels that release photons occurring extremely fast and hard to control. The THz band exists in a region of the EM spectrum where the technological advancements do not meet. This region of space is also known as the THz band ‘gap’.

Knowledge of how the THz wave propagates by channel modeling is essential for the development of reliable communication systems with high data rates. In our previous works we demonstrate wideband and directional channel measurements in the millimeter wave (mmWave) bands for 5G indoor LoS and NLoS Scenarios [9], [10]. In these studies the path loss, power attenuation and multipath propagation are measured and the results are presented in the form of PDP, RMS delay spread and excess delay. While the mmWave band has been thoroughly investigated, models developed in the lower THz band have been limited by the narrow bandwidth and lack of high frequency generation. These models need to consider molecular absorption as the most important propagation phenomena. In [11] channel measurements are presented in the 300 GHz band for two indoor scenarios with 10 GHz bandwidth using a Schottky diode based measurement system. LoS measurements at various separation distances up to 40 cm with material placed in between receiver and transmitter are conducted, from which the absorption coefficients of different materials are calculated. Diffraction at an edge measurements and interference investigation analysis are also conducted. It is shown that symbol rates of up to several 10 GSymbols/s can

Fig. 1: Specific attenuation for the frequency range 1-1000 GHz.

be achieved. In [12] the train-to-infrastructure (T2I) channel is characterized at 304.2 GHz center frequency with 8 GHz bandwidth. The PDPs are generated which can provide data on how trains affect the communications channel. This data is presented by calculating the Rician k -factor and RMS delay spread. Furthermore, in [13] channel characterization is extended up to 650 GHz using frequency up-converters and the results are compared with measurements in the 350 GHz band for indoor communications. PDP and power angle profile (PAP) are presented and the channel capacity is calculated. The results obtained for the PDP at both 350 and 650 GHz show that any multipath components introduced are of minor significance.

To the best of our knowledge, channel measurements conducted in the lower end of the THz band have been limited by the lack of high frequency generation and narrow bandwidth availability which does not allow for accurate and efficient characterization of the channel. In this paper, we present LoS measurements at high frequencies from 500 to 750 GHz with an ultra-wide bandwidth of 250 GHz considering a small delay resolution of 0.004 ns which allows for accurate channel characterization with high timing accuracy. The setup consists of a Tx and Rx arranged in a LoS configuration from which we obtain the s -parameters. The data obtained is further analysed by presenting the PDP while considering the effects of multipath propagation and molecular absorption. The measurements have been conducted at the National Physical Laboratory (NPL), Teddington, UK.

II. BACKGROUND

The absorption of EM waves in the atmosphere by oxygen and water molecules can be described as the specific attenuation of a signal propagating in free space. The specific attenuation considers various conditions that may affect signal propagation such as pressure, temperature and humidity. The ITU-R p.676-10 model for attenuation by atmospheric gases [14] calculates this attenuation by summing the individual resonances occurring from water vapor and oxygen particles. Additional factors are considered in the model for the non-resonant Debye spectrum below 10 GHz, pressure-induced nitrogen attenuation above 100 GHz and a wet continuum to account for the excess water-vapor absorption found experi-

Fig. 2: Channel measurement setup for the 500-750 GHz frequency range.

mentally. The specific attenuation due to atmospheric gases is given in (1) where γ and γ_ω are the specific attenuations resulting from the effects of water vapor and oxygen. $N''(f)$ is the imaginary part of the complex refractivity given in (2).

$$\gamma = \gamma_0 + \gamma_\omega = 0.1820fN''(f) \text{ dB/km} \quad (1)$$

$$N''(f) = \sum_i \sigma_i F_i + N_D'' \quad (2)$$

σ_i is the strength of the i -th resonant line. F_i is the line shape factor and N_D'' is the dry continuum due to pressure induced nitrogen absorption and the Debye spectrum. The specific attenuation in the 1-1000 GHz range has been calculated and is presented in Fig. 1. In the simulation, we assume pressure of 1013 hPa, temperature of 20° C for the case of a water-vapor density of 7.5 g/m^3 implying standard atmospheric conditions. From Fig. 1 we can observe that the levels of attenuation are increased as we go up in frequency. More specifically, for the frequency range of interest (500-750 GHz) two peaks are observed on the plot where the signal propagating will experience high levels of attenuation at 557 and 750 GHz, respectively.

III. MEASUREMENT CALIBRATION

For the S -parameter measurements, a Keysight Technologies PNA-X vector network analyzer (VNA) is configured with two Virginia Diodes Inc (VDI) and extender heads fitted with WM-380 [15] waveguide test ports. These extender heads operate from 500 GHz to 750 GHz. These measurements would be later post-processed to calculate the power delay profile of the channel.

Fig. 3: Channel coefficient measurements. (a) S_{21} for different Tx-Rx separation. (b) S_{21} for 1-inch Tx-Rx separation.

The VNA / extender heads combination was calibrated using a Short, Offset-short, Load and Thru (SOLT) technique using standards from a VDI calibration kit. The short, offset-short and load are one-port devices that are used as reflection standards. The standards correct for errors in the measurements due to system directivity, source mismatch and reflection tracking. The thru connection is effectively a null two-port device and is used, along with the reflection standards, to correct for errors in the transmission measurements (e.g. load match, transmission tracking and crosstalk errors) [16]. The performance of these standards has been verified previously against UK primary national reference standards thus establishing metrological traceability to the international system of units (SI) for these measurements [17].

The extender heads have a measured dynamic range of better than 80 dB (for an IF bandwidth of 10 Hz) and a test port power of -25 dBm [18]. Following the calibration, a pair of VDI WM-380 diagonal horn antennas were attached to the calibrated waveguide reference planes of the extender heads and both the extender heads along with the diagonal horn antennas were positioned facing each other in line-of-sight-mode as shown in Fig. 2. At these frequencies, the measured S-parameters between the horn antennas are very sensitive to positional inaccuracies. Hence X Y axis manual translation stages with 10 m accuracy [19] and rotation positioners [20] were used for each extender heads to ensure good LOS alignment between the boresight of the two horn antennas by maximizing the measured S_{21} .

IV. POWER DELAY PROFILE

The PDP represents the intensity of a signal received as a function of time delay between different multipaths. To generate the PDP for a LOS scenario, the channel coefficient is measured initially for different Tx and Rx separation distances as shown in Fig. 3(a). The measurement is conducted without any obstructing material affecting the signal propagation. As expected, the signals show high levels of atmospheric attenuation at 557 due to molecular absorption by water and oxygen particles. The attenuation dip at 750 GHz is not clearly observable due to the lack of measurement data above this frequency. Moreover, as the separation between the transmitter

and receiver increases, the signal strength decreases, and the atmospheric attenuation becomes more apparent at the frequencies where the specific attenuation peaks.

Furthermore, the attenuation losses affecting the signal propagation are considered and normalized. In this way the dips go away as shown for example in Fig. 3(b) for 1-inch Tx-Rx separation. From the measurements of the channel coefficient, we can derive the PDP by finding the inverse fourier transform of the channel coefficient. Fig. 4 illustrates the measured received power for various antenna separation distances considering a delay resolution of 0.004 ns given 1600 data points. Due to the very small delay resolution, individual multipaths can be resolved with a difference in propagation distance as small as 1.2 mm. It can be observed that as separation distance increases, it takes longer for the signal to be received and therefore the pulses on the figure are seen to shift. These pulses represent the power at the receiving side. For brevity the received power is shown for 0,2,4,6 inch separation since the same pattern would be observed for the rest of the measurements. Two other pulses can be observed for each measurement other than the LoS component with decreased power levels of around -40 dB. In order to understand where these pulses come from we need to analyze the PDP. In Fig. 5, we can see the PDP peaks for the thru and largest antenna separation distance measurements at 0-inch and 9-inch separation. The results for the rest of the measurements

Fig. 4: Received power for different Tx-Rx separation distance with absorption.

Fig. 5: Power delay profile for thru and 9 inch Tx-Rx separation distance.

has been omitted since they have similar characteristics as with 9-inch Tx-Rx separation. The first delay tap which is also the most dominant, is the LOS component. It occurs at 0 ns and 0.76 ns for 0-inch and 9-inch separation, respectively. Furthermore, at 9-inch separation, delay taps can be observed about 0.52 ns after the main delay tap which corresponds to 150 mm delay line. This particular component is a group delay product as it has comparable delay and is still relatively 40 dB down at the thru measurement too. A delay tap can also be observed at 2.5 ns which corresponds to 300 mm and may be a reflection off the bench. Other delay taps that appear may be reflections from the equipment. It can also be observed from the figure that the molecular absorption has no significant effect on the PDP since the waveform is not affected enough to introduce other components in our analysis.

V. CONCLUSION

Ultra-Wideband directional channel measurements have been conducted at LoS between Tx and Rx at 500-750 GHz. The delay resolution considered was 0.04 ns while at the Tx and Rx side highly directional antennas have been used. The channel characteristics in terms of specific attenuation of the signal due to molecular absorption have been considered. The PDP is presented for different Tx-Rx separation distances with and without molecular absorption. Multiple delay taps were introduced caused due to group delay product and reflection off the bench.

Limitations of this study include the short-range communication distance due to the low levels of received power which may not be applicable in realistic indoor communication scenarios. Future work based on the outcomes presented in this paper may be, e.g., modeling the reflection and scattering behaviour of different material in an NLoS scenario by analysing the temporal characteristics of the multipath channel such as RMS delay spread and coherence bandwidth.

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