Power Angular Measurements and Ray Tracing Simulations at Sub-THz Frequencies in Corridor

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Abstract—Ultra-wideband terahertz (THz) wireless communication systems are anticipated as a promising solution for applications with high bandwidth requirements in an indoor environment. To design the communication system operating at THz or sub-THz frequencies, it is important to acquire fundamental knowledge about the radio propagation characteristics at those frequencies. The main target of this paper is to conduct power angular spectrum (PAS) measurements at sub-THz frequencies of 90, 95, and 100 GHz in a line-of-sight (LOS) office corridor environment, and validate the ray tracing (RT) simulation results with the measurements. A sophisticated photonics-based measurement setup with high accuracy is utilized for measurement, whereas, an in-house built RT tool is used for simulation. The PAS is measured and simulated at eight different locations and a decent agreement is achieved between both. Whereas the other channel characteristics like root mean square delay spread (RMS-DS) and angular spread (RMS-AS) are only investigated through RT simulations. In the case of direct orientation, the root mean square error of about 1.5, 0.9, and 3.7 dB is found between the measured and simulated received signal power level at 90, 95, and 100 GHz, respectively.

Index Terms—Measurements, simulations, power angular spectrum, ray tracing, terahertz, THz.

I. INTRODUCTION

The next-generation communication systems are expected to offer at least 10–100× better throughput compared to fifth-generation (5G) communication systems and are anticipated to provide a data rate of around 1 Tbps for bandwidth-hungry applications such as holographic communications, augmented and virtual reality, etc. [1]. Ultra-broadband terahertz (THz) and sub-THz communication systems are foreseen to satisfy that need of 1 Tbps data rate. Several frequency bands are available at sub-6 GHz frequencies, mid-band, millimeter wave (mmWave) frequencies, sub-THz band, and THz band. It should be noted that lower bands provide better coverage, and higher bands provide larger bandwidth. Whereas, sub-THz frequencies (90-100 GHz) can be considered as a good compromise as it provides sufficient bandwidth for ultra-fast wideband transmission with short and medium-range [2]. The frequency band around 90-100 GHz can be effectively used for ultra-dense indoor small cell deployments for wireless access e.g., in the living room, conference room, office corridor, data center, etc, or can be used to provide a flexible extension to existing wired transport or backbone links.

Basically, in a LOS scenario, the sub-THz band can be used along with antennas with high gain i.e., over 25 dBi to overcome high free-space and reflection loss. To better design the system operating at the sub-THz band, it is imperative to understand the propagation mechanism at those frequencies. In an outdoor environment, atmospheric absorption is one of the main concerns for the sub-THz band, however, it has no or negligible impact on indoor propagation [2]. Therefore, in an indoor environment, like other lower frequency bands, the main propagation mechanism are specular reflection, diffraction, and diffuse scattering at the sub-THz band [2].

Ray tracing (RT) simulations help in generating accurate channel models with significantly less effort and higher flexibility than performing actual measurements [3]. In literature, studies related to channel measurements together with RT simulations around 100 GHz frequencies are generally limited, especially for the office corridor environment. Most of the studies targeted short distances i.e., from 60cm up to 5.5m in office or conference room environment [3]–[5]. Chia-Lin Cheng conducted measurement and characterized the propagation environment of an interesting case of a data center, whereby, the THz link is used for wireless rack-to-rack and blade-to-blade communication [6], and this measurement campaign was also limited to 2.1m only. In reference [7], authors characterized the propagation environment of a conference room at 190 GHz with the help of measurements along with RT simulations. Similarly, an exercise of validating RT simulation results with measurement data at 300 GHz is carried out in [8], where they considered a simple scenario of a small office room with only one reception (RX) point. Ke Guan et al. used channel-sounding measurements and RT simulations at 300 GHz for characterizing a special case of intra-wagon scenario, and provided path loss, power delay profile, delay spread, and shadow fading of the environment [9].

In this paper, we are mainly targeting to study the radio propagation characteristics of 90-100 GHz frequency band from the perspective of applications with medium-range requirement i.e., from 5 – 30m in a LOS indoor scenario. For this purpose, we carried out a comprehensive campaign of measurements and RT simulations. A sophisticated photonics-based measurement setup is utilized to obtain power angular spectrum. In this work, the authors have developed a stan-


dalone 3D ray tracing tool in MATLAB, and RT simulation results are validated with the measurements performed in an office corridor at sub-THz frequencies of 90, 95, and 100 GHz.

II. MEASUREMENT SETUP AND SCENARIO

The schematic diagram of the measurement setup used for the generation and detection of the signal at sub-THz frequencies i.e., 90, 95, and 100 GHz, is shown in Fig. 1. Measurement setup comprises of two sections: transmission and reception. For transmission, a photonics-based technique is employed for the generation of RF carrier wave frequency $f_C$. The major advantage of such systems is the ease of frequency tunability over a wide range of frequencies using the same set of components, and the ability to carry the RF signals over large distances, which cannot be achieved with conventional electronics. Since a simple optical heterodyne technique involves two free-running continuous-wave (CW) lasers, this results in considerable frequency instability and spectral drifting over time [10]. Whereas, in our measurements, external modulation technique [11] is employed to stabilize the frequency of carrier wave signal.

At transmission side, the optical carrier $\lambda_0$ is generated by a CW tunable laser source (TLS, Sacher Lasertechnik TEC-520-1550-030) operating at 1550nm telecom band, which is fed into a 50GHz electro-optic amplitude modulator (EOAM). The optical carrier $\lambda_0$ is modulated with an RF signal $f_{RF}$ provided by an external commercial signal generator (Keysight E8257D). The suppression of $\lambda_0$ is achieved by biasing the EOAM at minimum biasing point $V_{min}$, leaving two sidebands as dominant modes, whose frequency difference results in the desired carrier frequency ($f_C = 2f_{RF}$). The primary benefit of this technique is that the stability and phase noise of the generated signal is directly related to that of the signal source. The resulting optical sub-carrier signal is amplified by an erbium-doped fiber amplifier (EDFA, Amonics AEDFA-PA-35-B-FA), and is then carried from the lab to the experiment site through 50m long optical fiber. A high-speed PIN photodiode ($U^2$T XPDV4120R) converts the optical signal into the RF domain. A custom-made WR-10 horn antenna with a wide half-power beamwidth (HPBW) and low gain is used to radiate the signal.

The radiation pattern of the transmit antenna at 90GHz is shown in Fig. 2(a). Parameters of TX and RX antennas vary with the frequency of operation and are given in Table I.

A calibrated electronic harmonic mixer was used to accurately measure the generated RF power $P_{TX}$ before transmission. A high-gain horn antenna (Anteral SGH-26-WR10) with narrow HPBW is used at the RX side to receive the signal. The radiation pattern of the RX antenna in horizontal and vertical domain at 90GHz is shown in Fig. 2(b). The RX module located at a distance $d$ from the TX utilizes a harmonic mixing technique to detect the power $P_{RX}$ at reception. A commercial power-calibrated harmonic mixer (R&S FS-Z110) connected to the receiving antenna down-converts the received signal from $f_C$ to an intermediate frequency. Finally, the electrical spectrum analyzer (ESA, R&S FSW50) is used to measure and record the power of the signal. To acquire 360° PAS in azimuth plane, the RX module is mounted on a programmable rotation stage and is rotated 360° with 5° step size.

![Fig. 1. Schematic diagram of the measurement setup used for the generation and detection of signal.](image)

![Fig. 2. Radiation pattern of, (a) TX antenna, and (b) RX antenna, at 90GHz.](image)

| TABLE I  | PARAMETERS OF TX AND RX ANTENNA. |
|---------|-----------------------------------|
|         | TX                                | RX                                |
|         | Max gain [dBi] | HPBW [°] | HPBW [°] | Max gain [dBi] | HPBW [°] | HPBW [°] |
| 90GHz   | 10.98  | 50.5   | 30      | 26.77  | 7.7  | 8.5    |
| 95GHz   | 11.48  | 48     | 47.5    | 27.24  | 7.7  | 8.5    |
| 100GHz  | 12.58  | 45.5   | 45      | 27.62  | 7.7  | 8.5    |
Fig. 3. Measurement environment with TX and RX front-end devices.

Fig. 3 shows the measurement environment with TX and RX front-end devices. Both, the TX and RX antennas were placed at the height of 1m above the floor. The RF front-end modules are synchronized and controlled from a remote location to ensure that there are no physical interruptions along the propagation path. We have considered eight different positions P1-P8 for measuring the PAS, and the location of each receiver point along with the dimension of the corridor is illustrated in Fig. 4. The relative position of the RX points in x-, and y-domain with respect to the TX, and their distance is given in Table II.

### III. Simulation Methodology

Ray tracing simulations exploit the spatial characteristics of the environment and help in better understanding the radio channel response. Available commercial RT tools are like closed boxes, and they don’t offer the freedom to make amendments and changes. Therefore, for this research work, we have developed our own three-dimensional (3D) RT tool based on image theory (IT) [12], and it considers line-of-sight (LOS) path, specular reflected paths from the wall, ground, and ceiling of the floor, diffracted paths from the corners of the walls and other objects, and diffuse scattering (non-specular) paths due to surface roughness of the walls and other objects in the environment. The standalone 3D RT tool is developed in MATLAB, and can be used for different indoor scenarios, such as conference rooms, lecture halls, large corridors, residential homes and flats, warehouses, indoor factory environments, etc. Ray tracing tool provides the power, time delay, and the directional information i.e., angle of arrival (AoA), angle of departure (AoD), direction of arrival (DoA), and direction of departure (DoD) of each path, those are useful in determining the root mean square delay spread (RMS-DS) and angular spread (RMS-AS) of the propagation environment.

The main target of this study is to validate the RT simulation results acquired from an in-house built RT simulation tool with the measurement data. Therefore, the measurement cases and scenarios discussed in Section II are simulated. An accurate geometry and dimension of the office corridor and wooden closet are used to model the simulation environment. Due to the high frequency of operation i.e., 90-100 GHz, we have considered the ray paths up to two reflections and one diffraction only, along with diffuse scattered paths. In our measurement, the TX and RX both are located in the same corridor, therefore, the penetrated paths are not considered in simulations. General parameters e.g., antenna heights of the TX and RX antenna, transmission power, frequency of operation, azimuth, and downtilt of the TX and RX antennas, are set in the simulations as were used during the measurements. Considering the geometry of the environment and other objects, the RT tool provides information about the ray paths between the two points i.e., TX and RX. Subsequently, in the post-processing of the simulation data, antenna radiation patterns of the TX and RX antennas are utilized for antenna masking over ray tracing data. For simulations, antenna radiation patterns in horizontal and vertical domains were obtained from the manufacturers of the antennas.

### IV. Results and Discussion

This section provides a comparison of the measurement data and acquired simulation results in terms of received power angular spectrum (PAS). The PAS shows the received power around 360° for the RX antenna pointed in different directions. As illustrated in Fig. 4, the receiver positions P1, P3, and P6 are in the straight line i.e., center of the corridor, and are located in the direction of the main beam of the TX. Therefore,
they are placed in one group, whereas, the receiver positions P2, P4, and P7 are located close to the wall of the corridor, and are put in another group. Fig. 5(a-c) shows the PAS of position P1 at 90, 95, and 100 GHz, respectively, where the x-axis is the DoA in degrees at the RX side, and the y-axis is the received power in dBm. It can be seen in Fig. 5(a-c) that the maximum power is received when the RX antenna is pointing at 270° in azimuth i.e., facing towards the TX antenna, and a pretty good match is found between the measured and simulated received power levels at 90 and 95 GHz in the direction of DoA in degrees at the RX side, and the y-axis is the received power in dBm. It can be seen in Fig. 5(a-c) that the maximum power is received when the RX antenna is pointing at 270° in azimuth i.e., facing towards the TX antenna, and a pretty good match is found between the measured and simulated PAS, especially at 95 GHz. The receiver position P6 is located at a distance of around 5 m from the TX, and there is a wall at the back of P6 at a distance of around 12 m. Fig. 5(d-f) shows the PAS for P3 at 90 GHz, (g) P3 at 100 GHz, (h) P6 at 90 GHz, (b) P6 at 95 GHz, and (i) P6 at 100 GHz.

Fig. 5. Measured and simulated power angular spectrum of position, (a) P1 at 90 GHz, (b) P1 at 95 GHz, (c) P1 at 100 GHz, (d) P3 at 90 GHz, (e) P3 at 95 GHz, (f) P3 at 100 GHz, (g) P6 at 90 GHz, (h) P6 at 95 GHz, and (i) P6 at 100 GHz.

Similarly, position P3 is located at a distance of 7.2 m from the TX, and Fig. 5(d-f) shows the PAS for P3 at three considered frequencies, respectively. There is a perfect match between the measured and simulated PAS, especially at 95 GHz. The receiver position P6 is located at a distance of around 21.6 m from the TX, and there is a wall at the back of P6 at a distance of around 12.5 m. Fig. 5(g-i) shows the PAS for P6, and surprisingly measurements have captured a strong reflected path from the back wall as the measured received power in the direction of the back wall is just 7–8 dB

They have an offset of few dBs i.e., overall few dBs better. Further investigation of the measurement equipment and setup revealed that in the case of slightly twisted cables, lower power is received at the photodetector. This phenomenon is also observed for P6 position at 100 GHz as shown in Fig. 5(i) where there is a difference of around 7 dB between the measured and simulated received power levels in the direction of DO as well as at 90° i.e., reflected path from the wall at the back.
lower compared with the received power in the DO. However, RT simulation provides considerably low received power i.e., around 13 – 14 dB lower power in the direction of reflecting wall at the back compared with DO.

Fig. 6(a-c) show the PAS for position P2 at 90, 95, and 100 GHz, respectively, where P2 is located at a distance of around 4.9m away from the TX. It is illustrated in Fig.4 that P2 is placed close to the wall of the corridor, and is located slightly off the main beam and at the right side of the TX. In Fig.6(a-c), the maximum power is received at the DoA of 255°, and it can be noted in Fig.6(a) that both measured and simulation results show that there is a local peak at 290° of DoA, which is due to a reflected path from the close-by wall. Again, the signal reflected from the back wall is captured well around 75° of DoA in both measurements and simulations. For P2 at 100 GHz, simulation results show a large variation compared with the measured data. Fig.6(d-f) show the PAS for position P4 at 90, 95, and 100 GHz, respectively, and P4 is located at a distance of around 9.8m. As P4 is placed on a slightly right side of the TX, the maximum power is received at the DoA of 280°. Due to the strong LOS path, the impact of the reflected path at 260° is not prominently visible. However, it is interesting to note that both measurement and simulation results show that there is a strong signal reflecting from the closet at the DoA of around 100°. Finally, Fig.6(g-i) show the PAS for position P7, where P7 is located at a distance of around 28.83m from the TX. There is a good match in the received signal power values of the measured and simulated data in the direction of DO at all three considered frequencies. However, one abnormality is observed at the DoA of 155°, as in Fig.6(g-i), the PAS acquired through RT simulation shows that there is a strong path coming from the corner of the wooden closet, whereas, there is no such path found in the measured data.
Table III shows the difference of measured and simulated received power levels in the direction of DO. The root mean square error (RMSE) between the measured and simulated received power level was found around 1.5, 0.9, and 3.7 dB at 90, 95, and 100 GHz frequency of operation, respectively. The large RMSE at 100 GHz is probably due to the measurement error induced due to the twisting of optical fiber, as this issue is earlier highlighted. It should be noted that for all the positions from P1-P8, in the direction of DO the received signal power was higher than −75 dBm. It means that the TX-RX setup for sub-THz frequencies considered in this paper can be effectively used for several indoor applications for distances up to 32m in a LOS environment. It is not possible to compute RMS-DS or RMS-AS with the measurement setup used in this work, however, they are computed using RT simulation data. Interestingly, for the considered measurement setup it was found that in the DO the maximum value of RMS-DS was below 10ns for the farthest position i.e., P8. As coherence bandwidth is inversely proportional to DS, therefore DS less than 10ns is translated into large coherence bandwidth. The angular spread was found increasing with the increase in distance between the TX and RX. Again due to the utilization of antenna with narrow HPBW at the RX side, the RMS-AS in the azimuth plane was limited to 3.8° for the farthest position.

V. CONCLUSION

This paper presented 360° power angular spectrum (PAS) measurements acquired through sophisticated and calibrated photonics-based measurement setup and validated the simulation results of an in-house built RT tool with the measurement data at sub-terahertz (sub-THz) frequencies i.e., 90, 95, and 100 GHz. The indoor office corridor environment is characterized at eight different positions in LOS, with a maximum 32m TX-RX separation. For most of the RX positions, a fairly good match was found between the measured and simulated PAS. In direct orientation (DO), the root mean square error (RMSE) of around 1.5, 0.9, and 3.7 dB was found between simulated and measured received signal power at 90, 95, and 100 GHz, respectively. The measurement setup was found sensitive to the handling of optical fiber, as the received power was decreased in the case of twisted optical fiber. Simulation results showed that even for the RX position with 32m TX-RX separation, in DO the value of RMS-DS was below 10ns, as an antenna with narrow HPBW is utilized at the RX. Similarly, the maximum value of RMS-AS in the azimuth plane was limited to 3.8°.

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