Outdoor and indoor path loss modeling at the sub-THz band

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Abstract—In this paper, we present new measurement results to model large-scale path loss at the sub-THz (141-145 GHz) band, for both indoor and outdoor scenarios. Extensive measurement campaigns have been carried out, taking into account both line-of-sight (LoS) and non-line-of-sight (NLoS) propagation. For all considered propagation scenarios, existing omni-directional and directional path loss model have been developed, based on the so-called close-in (CI) free-space reference distance model. Moreover, path loss modeling is applied for the 2nd and 3rd strongest multipath components (MPCs). Thus, path loss exponent and large-scale shadow fading estimates are provided. Moreover, power angular spread analysis is derived using up to the 3rd strongest MPC.

Index Terms—Path loss exponent, indoor/outdoor environments, large scale fading, power angular spread.

I. INTRODUCTION

Sub-THz communications systems, operating at frequencies of above 100 GHz and close to the THz band, have recently attracted significant attention within both the wireless research community as well as for commercial purposes. The ever increasing demand for extreme high data rates has already pushed the current sub-6 GHz telecommunication systems to their limits. Sub-THz communications are therefore envisaged to fulfill the requirements for high data-rate communications and successfully complement telecommunication systems operating at lower frequency bands [1], [2].

Accurate modeling of channel and propagation characteristics is crucial for the performance analysis and design of telecommunication systems operating at such bands. However, to the best of our knowledge, very few studies on channel and propagation characteristics for frequencies above 100 GHz are available in the open technical literature. In particular, a number of important wireless propagation parameters, including path loss, gas attenuation and diffraction, require in-depth research. Among others, large-scale path loss analysis and modelling for indoor as well as outdoor environments are of significant importance. Representative examples can be found in [3]–[12].

As an example authors in [17] calculate path loss exponent at 73 GHz, for indoor and outdoor Airport environments, using only LoS links.

Lastly, power angular spread can provide useful information, which can be used to predict the angle of arrival (AoA) of each MPC, and in some cases to estimate receiver-transmitter antenna distance. For example in [18], the authors use power angular profile data to predict the arrival angles in a lecture room scenario for frequencies up to 300 GHz. Additionally, in [19], power angular profile provide information about the correlation of transmit-receive antenna distance, depending on the surrounding environment, as well as the propagation conditions.

Contributions: Motivated by the above studies, in this work we investigate path loss modeling at 140 GHz based on extensive channel measurement campaigns conducted in indoor and outdoor environments including LoS and NLoS links. Path loss modeling is provided for directional and omnidirectional case as well as for the 2nd and 3rd strongest multipath components. Finally, the angular power profile is analysed.

II. RADIO CHANNEL MEASUREMENTS

The channel sounder employed in the radio channel measurements is discussed in [20]. There are some differences in the sounder parameters used in each scenario as listed in Table I. The descriptions of each measurement site are elaborated in the following subsections.

A. Indoor Measurement Campaign

The measurement campaigns performed in the shopping mall and airport check-in hall are described in [10]. The third indoor site, which is further described in [21], is in the entrance.
TABLE I

| Measurement Detail | Shopping Mall | Airport | Entrance Hall 1 | Entrance Hall 2 | Suburban | Residential | City Center |
|-------------------|--------------|---------|-----------------|-----------------|----------|-------------|-------------|
| RF (GHz)          | 141.5-145.1 | 141.5-145.1 | 140-144 | 140-144 | 140-144 | 140-144 | 140-144 |
| Tx Antenna Height (m) | 1.89 | 1.7 above 2nd floor | 1.85 | 1.85 | 1.85 | 1.85 | 2.00 |
| Rx Antenna Height (m) | 1.89 | 2.1 above 3rd floor | 1.85 | 1.85 | 1.85 | 1.85 | 2.00 |
| EIRP (dBm)        | −12 | −12 | 5 | 5 | 5 | 5 | 5 |
| Rx Azimuth Range (°) | 0-360 | 0-25, 245-360 | 40-250 | −90-180 (Rx1); 40-250 (Rx2); 110-290 (Rx3) | 0-355 | Mostly 0-355 | Mostly 0-355 |
| Azimuth Step (°)  | 6 | 5 | 10 | 5 | 5 | 5 | 5 |
| Number of LOS Links | 16 | 10 | 2 | 12 | 32 | 13 | 19 |
| Number of NLOS Links | 2 | 1 | 9 | 56 | 8 | 42 | 21 |
| Environment Type  | Indoor | Indoor | Indoor | Indoor | Outdoor | Outdoor | Outdoor |
| Link Distance Range (m) | 3-65 | 15-51 | 3-47 | 3-66 | 2-172 | 20-175 | 10-178 |

The second measurement campaign was performed in a residential environment along Leppavaarankatu, Espoo, Finland. The street is mostly surrounded by residential buildings and by some commercial buildings. Metallic street posts and trees can also be found in the area. The antenna locations for this residential area are shown in Fig. 4.
The last outdoor measurement campaign was performed in an urban environment in the city center along Aleksanterinkatu, Helsinki, Finland. The street is surrounded by commercial buildings on both sides, forming a street canyon. The street is primarily intended for pedestrians, blocking vehicular traffic except for trams. There are rare metallic sign posts found on the street. The location has heavy loads of pedestrians traffic except for trams. There are rare metallic sign posts

Closely-spaced antenna locations were positioned at the building corners 1 and 2. In all Tx-Rx links, particularly of outdoor scenarios, the presence of moving objects is inevitable during the measurement of directionally-resolved wideband channels. Moving objects affect only a portion of directionally-resolved channels and may block some propagation paths. Our measured channels are therefore snapshots of channels with resolved channels and may block some propagation paths. Our measured channels will be referred to as omnidirectional modeling assuming non-coherent summation of multipath components; iii) the 2nd and the 3rd strongest multipath components for each link. Based on (1), path loss modeling estimates PLE equal to 2 with standard deviation 

where $\phi_i$ is the azimuth angle of arrival of the $i$-th MPC taking values from $0$ to $2\pi$ and $P_i$ is the corresponding power gain. Both equations are applied for every $Tx-Rx$ antenna link.

IV. PATH LOSS MODELING AND ANGULAR CHANNEL PROFILE

In this section, path loss measurements and the corresponding modeling will be presented for both indoor and outdoor environments. Path loss modeling is performed taking into account: i) the strongest multipath component for every link, which will be referred to as directional modeling; ii) the sum of all multipath components for each $Tx-Rx$ link, which will be referred to as omnidirectional modeling assuming non-coherent summation of multipath components; iii) the 2nd and the 3rd strongest multipath components for each link.

TABLE II

| Path loss modeling | LoS | NLoS |
|--------------------|-----|------|
|                     | PLE (n) | $\sigma$(dB) | PLE (n) | $\sigma$(dB) |
| Directional        | 2     | 1.8   | 2.9   | 9     |
| Omnidirectional   | 1.9   | 1.5   | 2.6   | 8.3   |
| 2nd Strongest MPC | 2.8   | 8.1   | 3.2   | 9.1   |
| 3rd Strongest MPC | 3.1   | 9.2   | 3.4   | 8.7   |

Specifically, as depicted in Fig. 6 for LoS links directional modeling estimates PLE equal to $n = 2$ with standard deviation $\sigma = 1.8$ dB for LoS and $\sigma = 2.9$ dB for NLoS.
deviation of $\sigma = 1.8 \, dB$. Omnidirectional modeling, when calculated non-coherently as in our case, is expected to represent the best case in terms of signal losses which is verified by the estimated $n = 1.9$ with standard deviation of $\sigma = 1.5 \, dB$. On the other hand, the 2nd and 3rd strongest MPCs can be modeled by larger PLEs, i.e., $n = 2.8$ and $n = 3.1$, respectively. Moreover, they are characterized by quite large values of shadow fading, that is $\sigma = 8.1 \, dB$ for the 2nd strongest MPC and $\sigma = 9.2 \, dB$ for the 3rd strongest MPC.

For LoS propagation and directional modeling, PLE is equal to $n = 2.0$ with standard deviation of $\sigma = 0.9 \, dB$. Non-coherent omnidirectional modeling yields a lower PLE, namely $n = 1.9$, with a slightly larger $\sigma$ of 1.1 dB compared to the directional case. The PLE values are quite similar to the corresponding ones for the indoor scenarios while $\sigma$ takes lower values in the outdoor case. The $2nd$ and $3rd$ strongest component analysis results in PLE of $n = 2.6$ and $n = 2.9$ with $\sigma = 9 \, dB$ and $\sigma = 8 \, dB$, respectively. Compared to indoor LoS links, PLEs have slightly lower values while standard deviations are similar.

As expected in Fig. 7, NLoS links are characterized by higher losses in all categories of path-loss modeling in Table II as expressed by the PLEs which are larger than the corresponding ones of the LoS case. In directional and omnidirectional modeling, significant increase is also observed in the shadow fading values which are now $\sigma = 9 \, dB$ and $\sigma = 8.3 \, dB$, respectively. For the 2nd and 3rd strongest MPCs, shadow fading values are comparable to those of the LoS case.

For LoS propagation and directional modeling, PLE is equal to $n = 2.0$ with standard deviation of $\sigma = 0.9 \, dB$. Non-coherent omnidirectional modeling yields a lower PLE, namely $n = 1.9$, with a slightly larger $\sigma$ of 1.1 dB compared to the directional case. The PLE values are quite similar to the corresponding ones for the indoor scenarios while $\sigma$ takes lower values in the outdoor case. The $2nd$ and $3rd$ strongest component analysis results in PLE of $n = 2.6$ and $n = 2.9$ with $\sigma = 9 \, dB$ and $\sigma = 8 \, dB$, respectively. Compared to indoor LoS links, PLEs have slightly lower values while standard deviations are similar.

B. Outdoor path loss modeling

Fig. 8 and Fig. 9 depict PLE as a function of $d$ after analyzing LoS and NLoS measurements of the outdoor scenarios. The same methodology was applied for outdoor measurements as in the indoor scenarios presented above. Thus, directional and omnidirectional path loss modeling is studied as well as for the $2nd$ and $3rd$ strongest MPCs. The corresponding results are available in Table III.
TABLE III
OUTDOOR LoS AND NLoS RESULTS FOR CI PATH LOSS MODEL

| Path loss modeling | LoS (Pd, dB) | NLoS (Pd, dB) |
|--------------------|-------------|---------------|
| Directional        | 2           | 0.9           |
| Omnidirectional    | 1.9         | 1.1           |
| Directional 2nd Strongest | 2.6         | 9             |
| Directional 3rd Strongest | 2.9         | 8             |

C. Power Angular Spread

Using Eq. (2) and Eq. (3), ASA values have been calculated for every Tx-Rx link of the available measurement sets. Then, the mean and standard deviation of $S_A$ have been calculated separately for LoS and NLoS links in indoor and outdoor environments, respectively. The results are given in Table IV where it is shown that the lowest mean value of $S_A$ is equal to 14° observed for NLoS links in outdoor environment and the higher mean value equals 23° for LoS links in indoor environment. These values are roughly in accordance with the statistics of directional channels in [25], where mean $S_A$ values of less than 20° are reported for indoor and urban environments. However, it is noted that [25] deals with below 6 GHz wireless channels.

TABLE IV
POWER ANGULAR SPREAD STATISTICS IN INDOOR AND OUTDOOR ENVIRONMENTS

| Environment | LoS mean ($S_A$) | LoS std ($S_A$) | NLoS mean ($S_A$) | NLoS std ($S_A$) |
|-------------|------------------|----------------|-------------------|-----------------|
| Indoor      | 23°              | 17°            | 18°               | 16°             |
| Outdoor     | 15°              | 14°            | 14°               | 14°             |

Moreover, it is observed that angular spread is larger in indoor environments compared to outdoor ones with mean $S_A$ being 23° vs 15° for LoS links and 18° vs 14° for NLoS links. Additionally, mean $S_A$ takes larger values for LoS links compared to NLoS ones for indoor measurements, namely 23° vs 18°. For outdoor environments, the values are very close, i.e., 15° vs 14°. Standard deviation of $S_A$ is concentrated within a narrow interval from 14° to 17° and thus the corresponding values are very close for indoor and outdoor environments, LoS and NLoS links.

Furthermore, indicative results for $S_A$ are given in Fig. 10 for every NLoS outdoor link of the measurement set. $S_A$ values are distributed around their mean value, which is 14° (denoted with dotted green line in Fig. 10) with standard deviation of 14° (see Table IV). It is also noted that, for some links the corresponding $S_A$ values are almost zero, indicating that the received power is dominated by the strongest MPC. Finally, there is no clear dependence between distance and angular spread.

V. CONCLUSION

In this paper, we have presented results on path loss modeling at 142 GHz, based on measurement campaigns conducted in both indoor and outdoor environments, providing estimations for path loss exponent and shadow fading. Path loss modeling has been also applied for the 2nd and 3rd strongest MPCs of the received signal, in order to gain insight regarding the spatial characteristics of the channel. Towards that direction, angular power spread has been also analyzed taking into account the 3 strongest MPCs. Mean $S_A$ values between 14° and 23° were observed, while the distance between $T_x-R_x$ does not seem to affect the power angular spread.

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