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Radiative Reference Plane Estimation and Uncertainty for THz Path Loss Measurements

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Abstract— A line-of-sight VNA measurement over 300 – 310 GHz with a separation of 10 – 340 cm, at 10 cm intervals was performed. The rms difference between the VNA results and Friis losses, calculated from distance measurements and Power-Delay Profile, was used to optimize the radiative reference plane correction. Optimal results were 10.1 mm (distance measurement) and 8.9 mm (PDP) for each antenna. This correction is significant for separations below 1 m.

I. INTRODUCTION

Power delay profile (PDP) is a valuable tool to measure channel characteristics, often using a channel sounder or a Vector Network Analyzer (VNA). The motivation is to improve the metrology in terahertz (THz) communications and thus improve the quality of RF channel models. Here, we use a calibrated VNA as the reference instrument.

In this paper we demonstrate the impact of radiative reference plane position on Friis-loss, direct-path calculations using physical distance and the PDP peak measurements. The transmission-loss can be calculated from the RF frequency and the distance using the Friis equation, following previous work by Tekbıyık et al [1]. The quality of fit gives an indication of the distance measurement accuracy as the VNA calibration reference-planes may not correspond with the radiation reference plane used for the Friis calculation.

II. PDP IMPULSE RESPONSE AND GAIN CALCULATIONS

The 10 GHz measurement bandwidth gives a time resolution of 100 ps, corresponding to a spatial resolution of 2.99 cm. The VNA is a frequency-domain instrument so the magnitude and phase of the forward and reverse transmission scattering parameters will be correct, but the PDP peaks may not correspond to the spatial grid-points set by the measurement bandwidth. The PDP for forward transmission signal (S_{21}) is based on the definition [2], with an additional frequency-domain windowing function $w(f)$:

$$PDP = |IFFT(S_{21}(f)\,w(f))|^2 \qquad (1)$$

Although the PDP results are in the time-domain they are presented here as propagation distances. Zero-padding to extend the maximum frequency is a computationally efficient way to reduce the grid-spacing location of the PDP peak. It also allows manipulation of the Fourier-Transform Radix to improve computational efficiency.

It is important to point out that windowing does not improve the resolution, which is linked to bandwidth [3].

A rectangular window has good resolution but high spectral leakage, masking smaller features in the PDP result. Higher dynamic range windows (Hann, and Hamming) will reveal these lower power features, but the peak estimation may be more sensitive to interference. The Tukey window has the convenient feature that it can be varied parametrically (α) from rectangular to Hann.

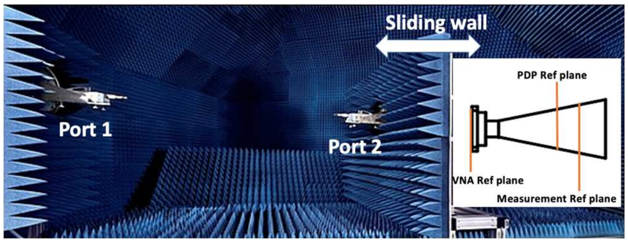

Fig. 1. Measurement setup using ZVA-Z325™ frequency converters placed on controlling motors holders. Port 2 moved successive steps away from port 1

The rms difference between the measured PDP peak and the calculated Friis was taken as our correction parameter, where the corrected offset distance provides the best fit. We also applied the rms difference between the mean measured magnitude and the calculated Friis magnitude.

The speed of measurement is important in many applications. The aliasing distance is defined by the frequency separation and therefore the number of points. Since there is an associated overhead with changing the synthesizer frequency, there is an additional speed benefit from using fewer points and a shorter aliasing distance.

Since the antenna gain is constant regardless of the measured distance. The combined gain of the antennas $G(f)_{dBi}$ is an average value of the Friis calculation leading to:

$$G(f)_{dBi} = \frac{1}{n}\sum_{i=1}^{n} S_{21}(f,d_i)_{dB} - PL_{corr}(f,d_i-\Delta d)_{dB} \quad (2)$$

where $S_{21}(f)_{i,dB}$ and $PL_{corr}(f,d_i-\Delta d)_{dB}$ are the VNA transmission results and the calculated path loss at each of the n antenna separation values(d_i), corrected for the reference plane offset Δd.

III. EXPERIMENTAL SETUP

The measurements were recorded in a temperature controlled anechoic chamber at PTB, shown in Fig.1. An automated control system varied the separation distance between the transmitter and receiver over the range (10 – 340) cm at 10 cm intervals. The initial separation measurement was made manually, and the subsequent results were reported by the instrumentation. The measurement duration for each spatial position, including the motors repositioning, was approximately 190 seconds. The relative humidity (RH) and temperature were recorded between $40.8\% - 41.6\%$, and $22.8\,°\mathrm{C} - 23.5\,°\mathrm{C}$, respectively. At 300 GHz, and this propagation path length, the humidity will have a negligible effect on the results [4].

The measurement system comprised a TRL calibrated Rohde & Schwarz ZVA24™ VNA with ZVA-Z325™ frequency converters and WR3.4 standard gain horn antennas at each port.

The S-parameter measurements comprised a linear frequency sweep of 1000 points covering 300 GHz – 310 GHz, at an IF bandwidth of 10 Hz.

IV. RESULTS AND DISCUSSION

The measurement performed in an anechoic chamber could not prevent the presence of multipath components in the measurements at short distances, where reflections from antennas surface and some absorbing materials were not avoidable. The ripple in the transmission signal magnitude due to unwanted multipath components is clearly shown in Fig. 2.

In the PDP result for a rectangular window the position of the multipath reflection is almost obscured. Applying a Hann window to increase the dynamic range and makes multipath component clearly visible.

To test the reference plane correction, a successive distance offset up to 10 mm was applied. The PDP peak rms difference between the optimum reference plane of Friis calculation and the VNA calibration reference plane was calculated, where rms difference between the curves in dB was used as the optimization metric. Fig. 3 shows the rms difference calculations along with Tukey window at $\alpha = 0$ (rectangular), $\alpha = 1$ (Hann), along with Hamming window. Zero-padding was tested as well for different interpolation factors. In Fig. 3 the windows suffered an increasing rms difference of 1.95 dB, 0.627 dB, and 0.8141 dB respectively. Different interpolations factors combined with rectangular window were tested along with the moving reference plane offset. Fig. 3 shows the rms deviation for factors $2, 4,$ and 40. The interpolation factor of 40, provided a grid-spacing of 0.74 mm, reduced the rms difference by 0.094 dB which indicates an improvement in the corrected PDP estimation. Merging zero-padding with Tukey ($\alpha > 0$), or Hamming windows produced a worse rms difference than rectangular window.

Moving the reference plane showed that the 10 cm distance is inconsistent with the other measurement values and having a great influence on the calculated rms difference. This can be due to the presence of an adjacent multipath components that could not be distinguished using our selected bandwidth.

We continued our rms analysis by moving offset correction up to 22 mm and taking the first distance out of our calculations. The results in Fig. 4 shows the minima for both distance measurement and PDP of 8.9 mm and 10.1 mm respectively per antenna, where the recorded rms fit improved to 0.029 dB for distance measurement, and 0.021 dB for PDP.

Analysing the total measured distances and calculating antenna gains as a common variable at each frequency step will give us an estimate for the antenna gain behaviour at the whole measured bandwidth. The mid-frequency of combined antenna gain, calculated from this dataset, was (40.44 ± 0.09) dB at 95% confidence, neglecting the reproducibility of the VNA calibration component. The standard horn has an increasing gain slope towards increasing frequency. Our measurement shows a slope of 0.027 dB/GHz as shown in Fig. 5.

V. CONCLUSION AND ACKNOWLEDGEMENTS

An optimisation of measured reference plane position has been applied to remove the systematic deviation from Friis in the line-of-sight VNA measurement. The Sinc (x) interpolation of the measured distances has been applied. The optimized reference provided a rms fit improvement from 0.17 dB to 0.029 dB (measurement distance) and 0.021 dB (PDP). The difference between PDP and measured distance planes will have implications for 2D and 3D channel sounding experiments to estimate the physical positions of transmitter and the receiver.

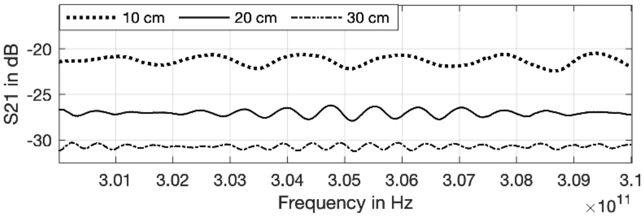

Fig. 2. $|S_{21}|$ measurement results for three separation distances show ripples due to multipath components.

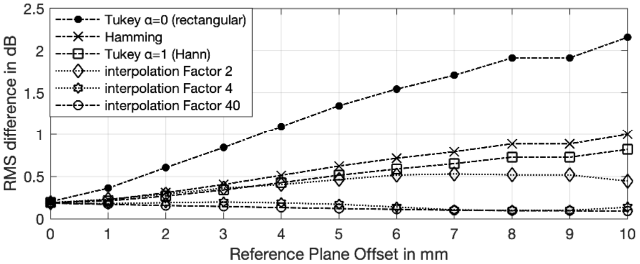

Fig. 3. PDP RMS difference in dB vs. successive reference plane offset comparison using raw, windowed, and interpolated measurements.

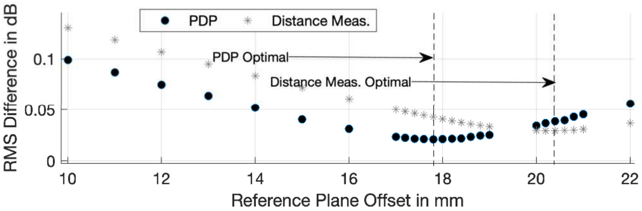

Fig. 4. PDP and measurement distance RMS difference in dB vs. successive reference plane offset comparison using Sinc (x) interpolated factor 40.

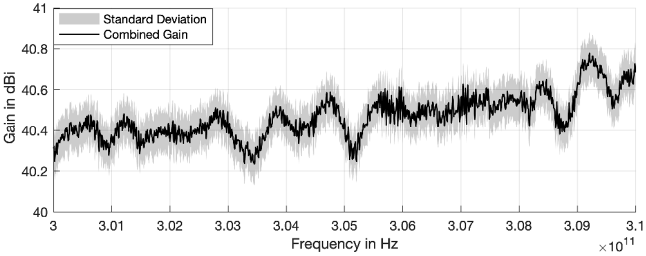

Fig. 5. Combined antenna gain calculated using measured transmission (VNA S_{21}) at all antenna separation values

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