Indoor Radio Channel Modeling at D-Band Frequencies

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***Abstract*—This paper presents indoor radio channel measurements and models at D-band frequencies. A Line-of-Sight (LOS) alpha-beta-gamma path loss model is created based on indoor measurements up to 8.5 m in a laboratory and office room, resulting in a floating intercept α of 34.2 dB, PL exponent β 1.9 and frequency dependency γ 1.9. The penetration losses for wood, acrylic, polyvinyl chloride (PVC) and glass are measured, resulting in a respective loss of 8, 3.5, 3 and 12 dB/cm. Furthermore, attenuation due to desk objects obstructing the LOS path is found to range from 3 to 10 dB for one or more universal serial bus (USB) cables, and 8 to 13 dB for a computer keyboard and mouse. A laptop screen completely blocks the LOS path. Therefore, we measured the attenuation of the reflected path when the LOS path is blocked, and conclude that desk objects provide valid fallback paths.**

***Index Terms*—radio propagation modeling, D-band, channel sounder, indoor, path loss, penetration loss, obstructed Line-of-Sight**

I. INTRODUCTION

With an increasing demand for high throughput wireless communication systems, wireless system engineers are looking at mmWave and sub-THz frequency bands where high bandwidths are available. However, radio channel modeling for typical indoor and outdoor environments is ongoing. This paper investigates the indoor radio channel at D-band frequencies, ranging from 110 to 170 GHz.

Indoor path loss (PL), penetration and reflection loss measurements at a 4 GHz subband centered around 140 GHz are presented by Xing et al. [1], [2]. For drywall, a reflection loss up to 9.8 dB is reported and the partition loss is found to be 8.5 dB. Fitting Line-of-Sight (LOS) PL measurements to a close-in PL model yields a PL exponent of 2. Olsson et al. present propagation and coverage measurements at 140 GHz in an office environment [3], reporting reflection losses up to 15 dB on wood, a penetration loss of 11 to 15 dB for drywall and 12 to 15 dB for glass. Aluminum and a computer monitor block the D-band test signal. The 140 GHz indoor radio channel in a shopping mall is characterized by Nguyen et al., providing an omni-directional PL floating-intercept model with PL exponent 2.2 and reference PL 70.8 dB at 1 m [4]. Pometcu et al. consider a 30 GHz subband, modeling the LOS and non Line-of-Sight (NLOS) radio channel for distances up to 10 m [5]. Cheng et al. and Kim et al. characterize the full D-band with a bandwidth of 60 GHz for distances up to 90 cm [6], [7]. Cheng et al. provide indoor path loss (PL) models and report an intercept value α of 25.4 dB, PL exponent β of 2.0 and frequency dependence γ of 1.4 when fitting measurement data to an alpha-beta-gamma (ABG) model [6]. Kim et al. report a reflection loss of 3 dB for an aluminum plate and 15 dB for fiberboard [7]. Dupleich et al. performed measurements in a conference room at 190 GHz and compared the spatio-temporal channel models to ray tracing simulations [8].

In this paper, we present indoor D-band channel measurements, covering the full 60 GHz bandwidth, for distances up to 8.5 m. The novelty of this paper is not only the creation of a Line-of-Sight path loss applicable to distances up to 8.5 m, we also present obstructed LOS measurements with typical indoor materials and objects obstructing the LOS path.

We start in Section II with a presentation of the channel sounder, which is validated in previous work [9], and a presentation of the measurement environments and scenarios. In Section III we provide the LOS PL model, followed by the attenuation for an obstructed LOS path and the presentation of reflected NLOS measurements. Section IV concludes this paper.

II. METHODOLOGY

A. D-band channel sounder

For the indoor channel measurement campaign we use the channel sounder from Fig. 1 which is presented and validated in previous work [9]. A vector network analyzer (VNA) generates a radio frequency source from 9.167 to 14.167 GHz which is upconverted to D-band frequencies using a frequency convertor that consists of a frequency multiplier as well as a harmonic mixer for the downconversion of the measured signal. The harmonic mixer uses a local oscillator signal from 11 to 17 GHz that is generated by an external signal generator. Standard gain vertically co-polarized horn antennas with a midband gain of 23 dBi and -3 dB bandwidths of 12.5° in the azimuth and 10° in the elevation plane are used as transmit (TX) and receive (RX) antennas.

We use 3001 frequency points, resulting in a frequency step size of 20 MHz. With the measurement bandwidth set to 100 Hz, this results in a sweep duration of 45 s, during which the environment is assumed to be static. Multiple frequency sweeps are performed and averaged.

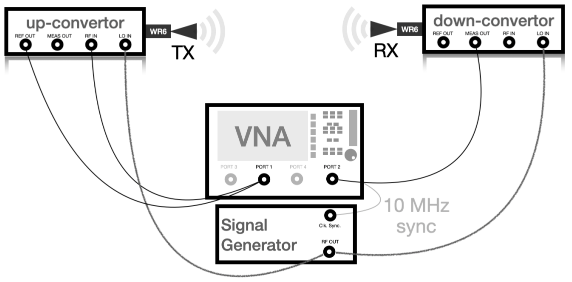

Fig. 1: Vector network analyzer (VNA)-based channel sounder architecture with a signal generator generating the 11 to 17 GHz local oscillator (LO) signal that is used by the harmonic mixer of the frequency convertors. Standard gain D-band horn antennas are connected to the frequency convertors' WR-6 waveguide.

The measured S_{21} scattering parameter is transformed into path loss (PL) via (1), with N the number of frequency sweeps, H the measured transfer function, G_a the antenna gain and C a correction term based on validation measurements [9].

$$\mathrm{PL_{dB}}(f) = -10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}|H_i(f)|^2\right)+2G_a(f)+C(f) \tag{1}$$

With this setup, we can measure path loss up to 105 dB for distances up 10 m.

B. Measurement environment

We performed measurements in three different indoor environments, i.e. a laboratory, a conference room, and an office room. The conference room measures 4 by 4.6 m with one wall made of glass, one wall made of wood and the two remaining walls made of drywall. One table is centrally placed. The office room measures 11.5 by 6 m, with walls made of drywall and plasterboard, and typical office room furniture being present, such as desks and chairs, desktop computers and monitors, amongst others.

C. Measurement scenarios

1) Line-of-Sight path loss: In the laboratory and office room, LOS measurements are performed with multiple distances between the TX and RX antennas. Along different measurement tracks, the distance is increased from 0.5 to 8.5 m, in steps of 10 cm. The two antennas are pointing towards each other. The measured PL samples are fitted to the alpha-beta-gamma (ABG) PL model from (2), with frequency f in GHz, distance d in meter, floating intercept α in dB, PL exponent β and frequency dependence γ. The shadow fading term χ_σ is based on the 95% percentile of a zero-mean normal distribution with standard deviation σ.

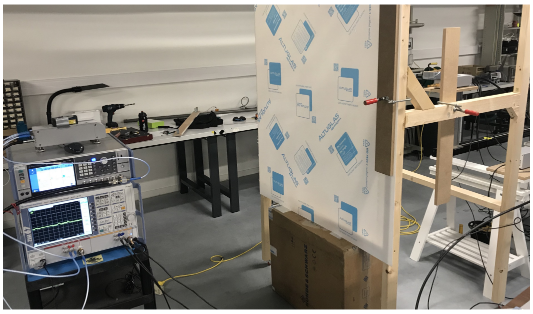

Fig. 2: Measurement setup for measuring penetration loss of a 3 mm thick acrylic sheet. Distance between the antennas is 2 m.

$$\mathrm{PL}(f,d) = \alpha+10\beta\log_{10}\left(\frac{d}{1\mathrm{m}}\right)+10\gamma\log_{10}\left(\frac{f}{1\mathrm{GHz}}\right)+\chi_\sigma \tag{2}$$

2) Penetration loss and object attenuation: We measure penetration loss of raw indoor materials, as well as attenuation due to typical desk objects obstructing the LOS path.

Penetration loss measurements are performed in the laboratory, with a distance of 2 m between the antennas, as well as a distance of 3 m, with the material under test (MUT) placed right in the middle. We considered medium-density fibreboard (MDF) wood, polyvinyl chloride (PVC), acrylic, and glass materials with dimensions exceeding 1 by 1 m. Due to the narrow antenna beam width and large material dimensions, only propagation through the material occurs [10]. There is no diffraction around the edges nor reflections caused by the environment. A picture of the measurement setup for acrylic is shown in Fig. 2.

We measure desk object attenuation in an office and conference room environment. The considered desk objects are one or more universal serial bus (USB) cables, a computer keyboard and mouse, a water bottle, a laptop and its power supply unit. Because of the smaller object sizes, we select a lower seperation of 0.5 m between the antennas and diffraction around the object occurs.

3) Reflected non Line-of-Sight path loss: Apart from attenuation due to a diffracted LOS path, we also consider attenuation of the reflected NLOS path. For this, we point the two antennas towards a reflection point on a nearby object or wall. The attenuation in addition to the LOS PL includes a reflection loss, which depends on the angle of incidence and the material of the object or wall, and a path loss due to the longer path length. This additional path loss caused by the higher path length is higher for smaller LOS path distances.

TABLE I: Penetration loss in dB per cm thickness for various materials, measured with a distance of respectively 2 and 3 m between the antennas, and averaged over 10 GHz subbands. No valid measurement data is available for acrylic with a distance of 3 m between the antennas.

Frequency	115 GHz		125 GHz		135 GHz		145 GHz		155 GHz		165 GHz	
Distance	2 m	3 m	2 m	3 m	2 m	3 m	2 m	3 m	2 m	3 m	2 m	3 m
Wood	5.7	6.2	6.0	6.4	6.8	6.7	7.8	7.3	8.4	8.5	9.3	9.3
PVC	2.6	2.6	2.9	2.9	3.2	3.1	3.5	3.4	3.9	3.8	4.2	4.1
Acrylic	4.5	-	2.7	-	3.5	-	4.9	-	3.6	-	3.7	-
Glass	8.4	8.3	9.3	9.2	9.9	9.9	11.0	11.0	11.9	11.9	12.9	12.7

TABLE II: Attenuation in dB due to desk objects obstructing the Line-of-Sight path, measured with a distance of 50 cm between the transmit (TX) and receive (RX) antennas, and averaged over 10 GHz subbands.

Object	115 GHz	125 GHz	135 GHz	145 GHz	155 GHz	165 GHz
Single USB cable	3.8	4.9	5.1	5.0	4.3	2.8
Multiple USB cables	10.7	8.7	6.8	5.4	3.9	3.3
Computer keyboard	8.3	8.4	7.8	8.3	8.2	8.3
Computer mouse	13.5	11.3	11.9	12.2	12.8	12.6
Water bottle	5.6	5.6	5.8	6.2	7.0	5.6
Laptop power supply	9.5	11.9	11.9	10.9	10.2	10.3

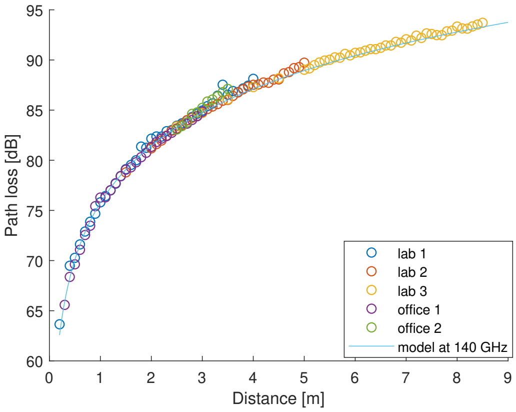

Fig. 3: Alfa-beta-gamma (ABG) path loss (PL) model and measurement samples at 140 GHz for 3 measurement tracks in the laboratory and 2 tracks in the office room.

III. RESULTS

A. Line-of-Sight path loss

Figure 3 shows the measured PL samples at 140 GHz for the different measurement tracks, as well as the fitted model evaluated at 140 GHz.

Fitting the measured LOS PL samples to the ABG model from (2) results in α = 34.57 dB, PL exponent β = 1.89 and γ = 1.92. The root mean squared error (RSME) between the fitted model and measured samples is 0.52 dB, which results in a shadow fading term χ_σ of 1 dB. The coefficient of determination of the fit R^2 is 0.993. The intercept α and frequency dependence γ are higher than the ABG model from Kim et al., but the PL exponent β is lower [7].

B. Line-of-Sight obstruction

The measured penetration losses for various materials are listed in Table I for the two distances. The listed values represent the loss per cm thickness of the material, i.e., free space PL is subtracted from measured PL and the resulting penetration loss is divided by the thickness of the measured material, averaged over 10 GHz frequency bands. Glass has the highest penetration loss, ranging from 8.4 to 12.9 dB/cm, followed by MDF wood, with penetration losses ranging from 5.7 to 9.3 dB/cm. The measured penetration loss for glass is lower than the 17 dB/cm reported by Xing et al. [2] but higher than values found by Olsson et al. [3]. The maximum difference between the averaged measured penetration loss with a distance of 2 m versus a distance of 3 m is 0.5 dB/cm, which confirms the accuracy of the measurement setup. Except for acrylic, the penetration loss increases with frequency.

Next to the penetration loss per cm thickness of some common materials, we also considered attenuation due to LOS obstruction by desk objects. The attenuation, averaged over 10 GHz frequency bands, is listed in Table II. Attenuation values range from 3 dB for a single USB cable up to 13 dB for a computer mouse. There is no frequency dependence.

C. Reflected non Line-of-Sight

Section III-B shows that an obstructed Line-of-Sight path can block D-band radio communication. Therefore, we investigate the path loss of the reflected NLOS path. In the laboratory and office room, the wall is made of plasterboard. In the office room, we also consider reflection on nearby objects. In the conference room, we consider reflection on a glass wall.

TABLE III: Measured Line-of-Sight (LOS) and reflected non-Line-of-Sight (NLOS) path loss (PL) in dB, with respective path lengths. NLOS PL is split into a distance-dependent term $\mathrm{PL}_{d,\mathrm{NLOS}}$ and reflection loss.

Room	Material	d_{LOS} [m]	$\mathrm{PL}_{\mathrm{LOS}}$ [dB]	d_{NLOS} [m]	$\mathrm{PL}_{\mathrm{NLOS}}$ [dB]	$\mathrm{PL}_{d,\mathrm{NLOS}}$ [dB]	θ_i [degrees]	Reflection loss [dB]
Laboratory	Plasterboard	4.0	87.3	5.0	96.0	89.3	50	6.7
Conference	Glass	2.6	83.7	4.8	97.5	89.0	32	8.5
Conference	Drywall	2.6	83.7	4.7	97.1	88.8	34	8.3
Office	Plasterboard	2.2	82.7	3.6	98.5	86.5	38	12.0
Office	Computer monitor	2.2	82.7	2.5	85.7	83.3	66	2.4
Office	Desktop PC	0.5	68.8	0.6	72.7	70.9	56	1.8
Office	Plastic box	0.5	68.8	0.6	75.1	70.9	56	4.2

An overview of all the LOS and reflected NLOS PL measurements is presented in Table III. We list the LOS path distance and measured LOS PL, followed by the NLOS path distance and measured NLOS PL. The latter is then split into path loss $\mathrm{PL}_{d,\mathrm{NLOS}}$ corresponding to the distance of the reflected NLOS path, and a reflection loss. We have calculated the angle of incidence of the reflection, based on the geometry of the measurement setup.

From Section III-A it is clear that LOS PL is close to free space PL, which is confirmed in the LOS measurements. Table III also confirms that a reflected NLOS path provides a fallback for D-band communication when the LOS path is blocked. A metallic enclosure of a desktop computer, a computer monitor and a plastic box are good reflectors, with reflection losses smaller than 5 dB. The calculated reflection loss for drywall of 8.3 dB corresponds well to the reflection loss of 7.5 dB for incident angle 30° reported by Xing et al. [2]. Plasterboard clearly has a higher reflection loss. The reflection loss of glass corresponds well to the reported values by Olsson et al. [3].

IV. CONCLUSION

In this paper, we have investigated the indoor radio channel at D-band frequencies, using a vector network analyzer-based channel sounder capable of characterizing the full D-band for distance up to 10 m. Line-of-Sight (LOS) measurements were performed in the laboratory and office room along multiple measurement tracks. Fitting the measured samples to an ABG path loss model results in an intercept value α of 34.6 dB, path loss exponent β of 1.9 and frequency dependence γ of 1.9. Penetration loss measurements were performed for PVC, acrylic, glass and wood for distances 2 and 3 m between the antennas. The maximum deviation between the measurement results of both distances is 0.5 dB/cm, which confirms the accuracy of the measurements. PVC and acrylic have low penetration losses, whereas glass has the highest penetration loss. In an office environment, desk objects such as computer peripherals or power supplies obstructing the LOS path cause an additional attenuation up to 13.5 dB compared to a non-obstructed LOS path. However, nearby objects such as a computer enclosure, monitor or plastic box can provide a fallback, due to the low reflection loss.

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