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Impact of Antenna Pattern and Reflective Environment on 60 GHz Indoor Radio Channel Characteristics

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Abstract—Wideband channel measurements at the 60-GHz frequency band in a reflective environment with different antenna heights are presented. The log-distance model of the normalized received power (NRP) is used to fit the measured data for both line-of-sight (LOS) and nonline-of-sight (NLOS) cases. Also, the impact of the biconical antennas and the reflective environment on the channel properties is analyzed and explained. Results show that the most favorable NRP values are found in the case that the Tx and Rx antennas are at the same height. Also, in most cases, the scatter paths have more contributions on the total received power than the direct path. In addition, in the LOS case, the NRPs become less dependent on the Tx-Rx separation owing to the combined effect of the antenna and the reflective environment. In the NLOS region, the contribution level of the strongest path becomes less dominant with increasing virtual Tx-Rx separation. The analysis of these results can be instructive for the deployment of a 60-GHz system in a reflective environment.

Index Terms—60 GHz, indoor radio communication, normalized received power, reflective environment, wideband channel measurement, wireless LAN.

I. INTRODUCTION

THE wideband millimeter-wave frequency spectrum around 60 GHz is of special interest for high data rate wireless local area network (WLAN) since tremendous bandwidth up to several gigahertz is available there [1], [2]. This frequency band is suitable for short distance communications, specially for indoor environment, due to a severe absorption attenuation at a range of 10–15 dB/km by oxygen molecules in the atmosphere. Additionally, both brick walls and concrete floors in an indoor environment can cause an attenuation of several tens of decibels, which limits an indoor cell to one floor in a building or even one room [3]. This offers the advantage that the frequency band can be reused at a short distance.

On the other hand, radio communications in the 60-GHz frequency band is limited by the link budget since the free space loss is very high compared to that in the low frequency band 2–5 GHz. Furthermore, if the receiver is located in the non-line-of-sight (NLOS) region, even more link budget is required due to the shadowing effect and the poor diffraction feature [3],

[4]. Nevertheless, in a small indoor environment, reflective objects and walls will induce more reflections and may therefore benefit the link budget.

This letter investigates the channel characteristics in a reflective indoor environment with many metallic objects based on channel measurements in the frequency band 57–59 GHz. Both the line-of-sight (LOS) region and the NLOS region are considered. The normalized received power (NRP) over log-distance is studied for different antenna heights. The impact of the antennas and the reflective environment on the channel properties will be analyzed and explained.

II. EXPERIMENTAL SETUP, REFLECTIVE ENVIRONMENT, AND MEASUREMENTS

The employed channel sounding system was based on an HP 8510C vector network analyzer. A detailed description of this system can be found in [5]. During measurement, the step sweep mode is used and the sweep time of each measurement is about 20 seconds [6]. The S_{21} transmission parameter has been measured in the frequency range from 57 to 59 GHz with 401 sample points. Complex channel impulse responses are obtained by Fourier transforming the S_{21} parameters into the time domain after a Kaiser window is applied with a sidelobe level of –44 dB. The resulting resolution of the channel impulse response in time domain is 1 ns.

The measurements have been conducted in a room with dimensions of $11.2 \times 6.0 \times 3.2$ m³. The top view of this room is shown in Fig. 1. The long sides and the door side are typical brick walls. The window side consists of window glasses with metallic frame ranging from 1 m above the floor up to the ceiling and a metal heating radiator below the windows. Outside the building, the windows are covered with a thin cool shade curtain made of copper (not depicted in the figure). The floor is made of concrete covered with linoleum and the ceiling is also made of concrete but covered with aluminum plates and light holders. Three aligned metallic cabinets are located in the middle of the room. To create a true NLOS area, the space between cabinets and ceiling has been blocked by aluminum foil. Other major metallic objects are the network analyzer itself and some metallic cable boxes attached to the walls.

A vertically polarized biconical antenna has been used at both the transmit and receive side. The antenna pattern is omnidirectional in the horizontal plane, the beam directivity is 9 dBi and the 3-dB beam width in the vertical plane is 9°.

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Fig. 1. Top view of the measured room.

To investigate the channel properties in this reflective environment, the complex channel responses were measured at different positions of the mobile receiver (Rx) in the LOS and NLOS regions. The antenna of the mobile receiver is at the height of 1.4 m. The transmitter (Tx) is fixed at a position as shown in Fig. 1 and its antenna can be located at three different heights, *viz.*, 1.4, 1.9, and 2.4 m.

III. MEASURED RESULTS AND ANALYSIS

The NRP is defined as the received power normalized to the transmitted power within the considered bandwidth. The NRP in decibel is just the reverse of the path loss, for which the log-distance model has been widely used [7]. Therefore, we will investigate the log-distance NRP model which is defined as

$$\text{NRP}_d \text{ (dB)} = \text{NRP}_{d_0} - 10n \lg(d/d_0) + X_\sigma \text{ (dB)} \quad (1)$$

where NRP_{d_0} is the NRP at the reference distance $d_0 = 1$ meter, $\lg(\cdot)$ is the log function with the base 10, n is the loss exponent, and X_σ is a zero mean Gaussian distributed random variable with the standard deviation σ .

A. NRPs in the LOS Region

Fig. 2(a) depicts the measured NRPs and fitted curves in the LOS region over log-distance between transmitter and receiver (see also Table I). The mean NRPs are -56.1 , -66.8 , and -73.1 dB for the Tx-antenna heights of 1.4, 1.9, and 2.4 m, respectively (see Table II). This means that with an increase of Tx-Rx height difference, the NRPs tend to reduce. This can be explained by the shape of the antenna pattern: increasing the height difference will reduce the gain for the LOS ray of both the transmit and receive antenna.

When transmitter and receiver are at the same height, the path loss exponent is smaller than the free-space value of 2, *i.e.*, 1.17, due to the large contribution of the reflections at the environment. When they are not at the same height (cases Tx at 1.9 and 2.4 m), the exponents are even smaller. Moreover, the exponent for the case Tx at 1.9 m is smaller than that for the case Tx at 2.4 m. The observations will now be explained.

First, notice that the measured NRP has contributions from the wave propagation along the direct path and from

Fig. 2. (a) The NRP values in the LOS region and (b) the part of the NRP values contributed by the direct paths over the log-distance of Tx-Rx.

TABLE I
CURVE FITS OF THE MEASURED NRPs OVER LOG-(VIRTUAL) SEPARATION BETWEEN THE (VIRTUAL) TRANSMITTER AND THE RECEIVER [REFER TO THE LOG-DISTANCE MODEL IN (1)]

Experiment	LOS region			NLOS region		
	NRP_{d_0}	n	σ	NRP_{d_0}	n	σ
$H_{Tx} = 1.4$ m	-50.3	1.17	2.7	-16.8	5.45	3.9
$H_{Tx} = 1.9$ m	-65.8	0.18	2.0	-38.7	3.82	3.3
$H_{Tx} = 2.4$ m	-69.8	0.61	1.3	-53.0	2.67	2.7

TABLE II
MEAN VALUES OF NRPs IN BOTH THE LOS AND NLOS REGIONS AND THEIR MEAN DIFFERENCES

Cases	LOS (dB)	NLOS (dB)	mean diff. (dB)
$H_{Tx} = 1.4$ m	-56.1	-71.1	15.0
$H_{Tx} = 1.9$ m	-66.8	-75.0	8.2
$H_{Tx} = 2.4$ m	-73.1	-77.7	4.6

the wave propagation along indirect paths (such as diffracted and reflected waves). The latter will be denoted by scatter paths. From the measured power delay profile, the direct path can be readily recognized. The power of the direct path NRP_{dir} with antenna gains included can be

Fig. 3. The ratio between the contributed powers by the scatter paths and the direct path over the Tx-Rx separation.

derived by adding up the powers within the resolution bin of 1 ns. The remain power NRP_{scat} within the profile is contributed by the scatter paths. With these two NRP-parts, the effects of the antenna pattern on NRP_{dir} and the reflective environment on NRP_{scat} can now be analyzed.

The direct path experiences the loss in free space and the gains from both the transmit and receive antennas. Fig. 2(b) depicts NRP_{dir} with the fitted curves over log-distance. It shows that when Tx-Rx are not at the same height, increasing the Tx-Rx separation will raise the received power of the direct path, while in the case Tx at 1.4 m the opposite can be observed. This is due to the narrow antenna pattern in the vertical plane. When the Tx-Rx separation increases, the gain of the biconical antennas for the LOS ray will increase at approximately the same rate for both the cases Tx at 1.9 and 2.4 m and compensate the free space loss, while the antenna gain for the case Tx at 1.4m remains constant.

To analyze the relative contribution of the reflective environment to the NRP_{scat} , we define the ratio between the powers contributed by the scatter paths and the direct path

$$G \text{ (dB)} = 10 \lg \left(\frac{NRP_{\text{scat}}}{NRP_{\text{dir}}} \right) \text{ (dB)}. \quad (2)$$

When the ratio G is much larger than 0 dB, the scatter paths become dominant in the total NRP instead of the direct path and vice versa. Fig. 3 depicts the ratio G over the log-distance. One can see that most of the values are above 0 dB except the case Tx at 1.4 m where the values are around 0 dB. In other words, the received power contributed by scatter paths is generally larger than the contribution of the direct path owing to the highly reflective environment. It is also clear that the scatter paths will compensate the NRP reductions in free space with increasing Tx-Rx separation. The bigger the Tx-Rx height difference, the more dominant the scatter paths become in the NRP. For the cases Tx at 1.9 and 2.4 m, the contribution of scatter paths is significant and increasing the log-distance will reduce the contribution until a level at which the scatter paths and the direct

Fig. 4. The NRP values in the NLOS region over the virtual Tx-Rx separation.

path are comparable. Meanwhile, the reducing speed of the contribution for the case Tx at 1.9 m is slightly lower than that at 2.4 m. This explains why the loss exponent for the case 1.9 m is smaller than that for the case Tx at 2.4 m in Fig. 2(a).

B. NRPs in the NLOS Region

For the NLOS receivers, there is no direct path from transmitter but the main contribution is due to reflections from the brick wall (side 2 in Fig. 1). By taking the brick wall as a mirror, the virtual transmitter in the mirror can see most of receivers in the NLOS region. Therefore, it is more meaningful to look at the NRPs over the separation between the virtual transmitter and the receiver than the real separation. The NRPs over the log-(virtual) separation are depicted in Fig. 4. Similar behaviors can be observed here as in the LOS region, i.e., that increasing the distance will reduce the NRPs and the NRP values in the case Tx at 1.4 m are generally higher than that in the other two cases. However, the fitted curves over log-(virtual) distance show much higher loss exponents and larger deviations of X_σ than that in the LOS region. Also, the mean NRPs are 15.0, 8.2, and 4.6 dBs lower than the mean values in the LOS region, as seen in Table II, for the cases Tx at three heights respectively. Furthermore, the mean NRPs, i.e., -71.1, -75.0, and -77.7 dB, are quite close to each other in contrast to the significant difference as seen in the LOS region. This implies that in the NLOS region the NRPs become less sensitive to the height difference between Tx-Rx antennas.

To gain more insight into the NLOS channel, we plot the NRP of the strongest path in Fig. 5(a), and the NRP ratio between the contributed powers by the scatter paths (except the strongest path) and the strongest path in Fig. 5(b). The fitted curves indicate that, in general, the strongest path becomes less dominant in the received power with increasing the virtual Tx-Rx separation. This trend is more obvious for the case Tx at 1.4 m.

IV. CONCLUSION

In this letter, the normalized received power values were measured in the frequency range 57–59 GHz in a reflective environ-

Fig. 5. In the NLOS region: (a) the NRP of the strongest path; (b) the ratio between the contributed powers by the scattered path (except the strongest path) and the strongest path over the virtual Tx-Rx separation.

ment. The log-distance model of the NRPs was used to fit the measured data. The impact of the antennas and the reflective environment on the NRPs was analyzed in detail. There are several conclusions that can be made from the measured results. First of all, the highest, thus the most favorable, NRP values can be found in the case that the Tx and Rx antennas are at the same height. Next, in the considered reflective environment, the contribution of the scatter paths to the total received power is more than that of the direct path in most cases, except for the case Tx-Rx antennas at the same level where the scatter paths and the direct path have a comparable contribution. In addition, the combined effect of the antenna and the reflective environment reduces the dependence of the NRP on the Tx-Rx separation in the LOS region. Moreover, in the NLOS region, the NRP values become less sensitive to the height difference between Tx-Rx antennas. The contribution level of the strongest path in the received power becomes less dominant with increasing virtual Tx-Rx separation. Lastly, the analysis of the reported results and observations in this letter can be instructive for the deployment of a 60-GHz system in a reflective environment.

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