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INFLUENCE OF FURNITURE ON THE 60 GHz RADIO PROPAGATION IN A RESIDENTIAL ENVIRONMENT

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Abstract:

At millimeter-waves, the home furniture and objects dimensions can be equal or superior to the wavelength. A comparison between propagation measurements conducted within a residential house for two configurations, furnished and empty, underscores the influence of the furniture on the millimeter-waves propagation.

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1. Introduction

The 60 GHz frequency band is a good candidate for future high data rate and short-range communications within indoor environments [1]. The wavelength ($\lambda \approx 5$ mm) is small in comparison with many objects dimensions in residential environments. Furniture and objects present many rough and smooth reflective surfaces and many diffracting edges. They are then likely to contribute to the propagation phenomena in furnished environments. In most of propagation studies, however, measurement environments are rarely furnished, and ray-tracing tools do not take into account the presence of the furniture. To our knowledge, only [2] compares wideband channel characteristics between an empty and a furnished room around 60 GHz. This comparison was performed in a rectangular room, with some basic pieces of furniture (tables, chairs, cupboards), in an office environment.

This letter compares the results of 60 GHz propagation measurements conducted within a residential house for two configurations: furnished (FC) and empty (EC).

2. Measurement setup

A. Equipment

The measurement campaigns were conducted by using a channel sounder based on the sliding correlation technique [3]. This sounder evaluates the complex impulse response (CIR) with a 2.3 ns temporal resolution and a 40 dB relative dynamic within a 500 MHz bandwidth. The width of the observation window of the CIR can be chosen up to 1 μ s. This width was set to 200 ns.

Three antennas were used: a horn, with a 22.4 dB gain and 12° Half Power Beamwidth (HPBW), and two patches, with a 58° HPBW, a 4.3 dB gain for the first one, and a 2.2 dB gain for the second one.

B. Environment

The measurements were performed in a typical European residential house (Fig. 1). The first floor dimensions were about 10.5×9.5×2.5 m (Fig. 2). The outer walls were 38 cm-thick (breeze blocks and plasterboard). The main internal wall was 17 cm-thick brick and plaster, and the others were 7 cm-thick plasterboard. The ceiling was made of concrete, and the floor was tiled. One found wooden stairs, a fireplace, carpets, curtains, double-glazing, and houseplants. Most of the furniture was made of wood.

C. Measurement scenarios

The transmitter (Tx) was placed in a corner of the main room, near the ceiling (2.2 m) and slightly tilted toward the ground (“TX1” in Fig. 2). Two receiver (Rx) locations were chosen in line of sight (LOS) and two others in non-LOS (NLOS), *i.e.* in adjacent rooms. For both FC and EC, the measurements were performed exactly at the same locations (to within about 1 cm).

The Tx antenna was always the first patch. The horn and the other patch were used successively in each Rx location, in vertical and then horizontal polarization. Therefore, for each Rx position, four antennas configurations were considered. Thanks to a motorized positioning system, the Rx

antenna was rotated over 360° for angles of arrival (AOA) analysis, by a step of 6° for the horn and 12° for the patch. This rotation was repeated along a 10 λ length linear track by a step of λ (a similar method was used in [4]). The Rx antenna had a null elevation angle. Nobody was present in the house during the measurements, except the operator who kept still behind the Tx antenna.

3. Comparison between EC and FC

A. Definitions

The received power (Pr) and several broadband characteristics – 90% delay window (DW₉₀), 75% coherence bandwidth (Bc₇₅) [5], number of paths (Nb_{paths}) – were computed for each measurement point. The number of paths was computed with the help of a detection algorithm of the local maxima of the CIR module. A 25 dB threshold under the most powerful path was used to reject insignificant paths. A spatial mean calculation along the linear track was performed to suppress the channel small-scale variations, and the positioning errors between FC and EC. Thus, we focused on the local mean characteristics. The difference between EC and FC was then evaluated and expressed in dB and in % as follows:

$$\varepsilon_{C_iAP(dB)}(\alpha) = 10 \cdot \log_{10} \left(\frac{C_fur_{iAP}(\alpha)}{C_emp_{iAP}(\alpha)} \right)$$

$$\varepsilon_{C_iAP(\%)}(\alpha) = 100 \cdot \left(\frac{C_fur_{iAP}(\alpha) - C_emp_{iAP}(\alpha)}{C_emp_{iAP}(\alpha)} \right)$$

where $C_fur_{iAP}(\alpha)$ and $C_emp_{iAP}(\alpha)$ are the values of a propagation characteristic C with respect to the angle of arrival α , respectively for FC and EC. Index A (Antenna) can be H (Horn) or P (Patch). Index P (Polarization) can be V (Vertical) or H (Horizontal). Index i indicates the Rx position number. A positive ε value means an increase of the considered characteristic when the furniture is added.

As an example, Fig. 3 shows $Pr_fur_{1HV}(\alpha)$, $Pr_emp_{1HV}(\alpha)$ and $\epsilon_{Pr_1HV(dB)}(\alpha)$. This kind of graphic can be correlated with the house plan. This makes it possible to better understand the influence of furniture.

We will focus on the LOS/NLOS differences because they are stronger than those of antennas configurations. We define several parameters to analyze the variations of the propagation characteristics. First, the 10th and 90th percentiles (P10 and P90) are computed from the Cumulative Distribution Functions (CDF) of the $\epsilon_{C_iAP(dB)}(\alpha)$ values. The percentiles are averaged over all the antennas configurations and positions, and listed in Table 1. These values give an overview of the spread of the variations between FC and EC. Two other parameters are defined: the mean global variations (ϵ) and the mean “distances” (δ) between FC and EC, shown in Table 2 and calculated as follows:

$$\begin{aligned}\epsilon_{C_i} &= \frac{1}{4} \left(\overline{\epsilon_{C_iHV(dB)}(\alpha)} + \overline{\epsilon_{C_iHH(dB)}(\alpha)} + \overline{\epsilon_{C_iPV(dB)}(\alpha)} + \overline{\epsilon_{C_iPH(dB)}(\alpha)} \right) \\ \delta_{C_i} &= \frac{1}{4} \left(\left| \overline{\epsilon_{C_iHV(dB)}(\alpha)} \right| + \left| \overline{\epsilon_{C_iHH(dB)}(\alpha)} \right| + \left| \overline{\epsilon_{C_iPV(dB)}(\alpha)} \right| + \left| \overline{\epsilon_{C_iPH(dB)}(\alpha)} \right| \right) \\ \epsilon_{C_los} &= \frac{1}{2} (\epsilon_{C_1} + \epsilon_{C_2}) & \epsilon_{C_nlos} &= \frac{1}{2} (\epsilon_{C_3} + \epsilon_{C_4}) \\ \delta_{C_los} &= \frac{1}{2} (\delta_{C_1} + \delta_{C_2}) & \delta_{C_nlos} &= \frac{1}{2} (\delta_{C_3} + \delta_{C_4})\end{aligned}$$

The ϵ values allow an overview of the global variation of the propagation characteristics, for a given Rx position (ϵ_{C_i}) and for each visibility situation (ϵ_{C_los} and ϵ_{C_nlos}). The ϵ values can be negative or positive.

B. Results

Fig. 4 shows the CDF of $\epsilon_{Bc75_2HV(dB)}(\alpha)$. The wide spread of the CDF can be noticed: about from -10 up to 10 dB. More than 30% of the $|\epsilon|$ values exceed 3 dB around 0 dB. Globally, the maximum variations of Pr (averaged over the antenna configurations) are -7.9 dB up to $+4.1$ dB when the furniture is added. These maximum variations spread from -92% up to $+350\%$ for $Bc75$.

Table 1 shows that these wide variations affect all the propagation characteristics, especially Pr and $Bc75$. For these two characteristics, the inter-percentile range P90-P10 is greater than 7 dB.

To look closer into the phenomenon, we consider the Rx1 case. Fig. 3 shows $Pr_fur_{1HV}(\alpha)$, $Pr_emp_{1HV}(\alpha)$ and $\epsilon_{Pr_1HV(dB)}(\alpha)$. From $Pr_emp_{1HV}(\alpha)$, four main directions of arrival can be distinguished:

- $\alpha_1 = 252^\circ$: AOA of the direct path;
- $\alpha_2 = 102^\circ$ and $\alpha_3 = 306^\circ$: AOA of two first order reflected paths;
- $\alpha_4 = 57^\circ$: AOA of a second order reflected path.

When the furniture is added, $\epsilon_{Pr_1HV(dB)}(\alpha)$ values show that Pr decreases by more than 5 dB for all of these AOA. For the direct path AOA, $\epsilon_{Pr_1HV(dB)}(\alpha_1) = -5.74$ dB. The combining of reflected paths (particularly one path on the floor) with the direct one explains this variation. When the furniture is added, the direct path is not affected, but the number of reflected paths grows, and thus the link budget is modified. In the other directions of arrival, Pr is constant or increases. The broadband characteristics, such as $Bc75$ (Fig. 5), and Nb_{paths} (Fig. 6) show that the frequency selectivity of the channel increases for the four main AOAs when the furniture is added. $Bc75$ decreases, sometimes dramatically (example: $\epsilon_{Bc75_1HV(dB)}(\alpha_2) = -16.7$ dB in Fig. 5). Nb_{paths}

increases by about 5 dB, from 1-2 paths to 4-5 paths. In the other AOAs, one can notice the opposite variation, or a null variation.

The ϵ_{C_1} values follow the variations of the main AOAs: $\epsilon_{Pr_1} = -0.98$ dB, $\epsilon_{Bc75_1} = -0.360$ dB (-8.0%), and $\epsilon_{Nbpaths_1} = +0.210$ dB ($+5.0\%$). This means the variation of the four main AOAs is not compensated by the opposite variation of the other AOAs. Similar observations are possible for Rx2, the other LOS position.

For NLOS situations, the broadband characteristics inversely vary (Table 2): $\epsilon_{Bc75_nlos} = +0.353$ dB ($+8.3\%$), and $\epsilon_{Nbpaths_nlos} = -0.679$ dB (-14.5%). The Pr variation, however, is negative, as for LOS situations: $\epsilon_{Pr_nlos} = -0.91$ dB.

The δ values present the mean absolute difference between the two configurations. Table 2 shows that this absolute difference is similar in LOS and in NLOS situations.

4. Discussion

Compared to EC, the received power in FC is lower, and the channel frequency selectivity is higher in LOS situations and lower in NLOS situations. These results indicate that the presence of furniture noticeably increases the energy dispersion within the Tx room (LOS situations). The furniture surfaces and edges create more wave paths ($\epsilon_{Nbpaths_los} = +0.346$ dB or $+8.3\%$) in more directions, entailing less powerful paths (globally $\epsilon_{Pr_los} = -1.77$ dB), greater delay spreads ($\epsilon_{DW90_los} = +0.092$ dB or $+2.2\%$), and lower coherence bandwidths ($\epsilon_{Bc75_los} = -0.598$ dB or -12.9%). Similar observations are reported in [2] for the number reflected rays and for DW_{90} . Moreover, the furniture hides parts of the walls and the floor, which are “quasi-specular” reflectors and which greatly contribute to the propagation within an empty room. Due to the

furniture, the Pr angular repartition is then more diffuse; in contrast, for EC this repartition is more concentrated in several main directions of arrival.

When the antennas are in different rooms (NLOS), most of the received energy comes from doors, as underscored in [6], because the propagation loss caused by the walls is very important. In NLOS situations, the following phenomenon is observed when the furniture is added: the channel frequency selectivity decreases ($\epsilon_{Bc75_nlos} = +16.2\%$, $\epsilon_{DW90_nlos} = +14.5\%$), and Pr decreases ($\epsilon_{Pr_nlos} = -0.91$ dB). This phenomenon can be interpreted as follows: in EC, the probability that *powerful* indirect paths going through doors exist is higher, because the walls and the floor are clear. Therefore, in adjacent rooms, Nb_{paths} is globally higher in EC. In FC, Nb_{paths} is higher in the Tx room but these paths convey little energy and eventually arrive in an adjacent room under the sounder noise level (-120 dBm).

5. Conclusion

Propagation measurements at 60 GHz were conducted in a residential environment for two configurations: with and without furniture. The results underscore the influence of the furniture. When ray-tracing tools neglecting the furniture are used or when measurements campaigns are performed in empty environments, one commits some errors if the results are used to describe realistic propagation conditions. The ϵ , δ , and percentile values can be seen as estimations of these errors. In these cases, the channel frequency selectivity within a room is underestimated, and it is overestimated for inter-rooms links. In both visibility situations, the received power is overestimated. The strongest erroneous estimations are noticed on the main directions of arrival. Despite the practical difficulties, it would be interesting to investigate other environments to complete these results.

Acknowledgement

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Figure captions:

Fig. 1: Photography of the measurement environment

Fig. 2: First floor of the measurement environment

Fig. 3: Comparison of the received power between FC and EC (Rx1, horn antenna, vertical polarization, LOS)

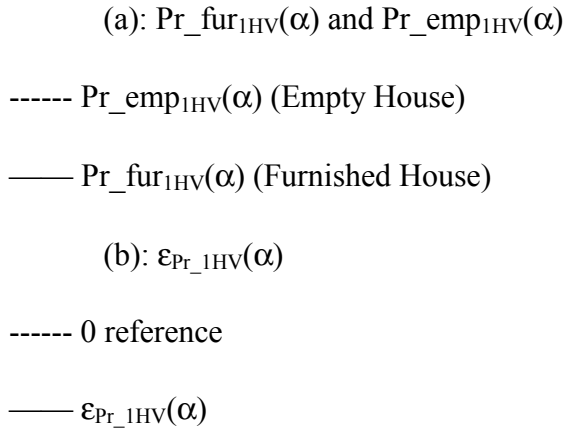


Fig. 4: Cumulative Distribution Function (CDF) of ϵ_{Bc75_2HV} (dB) (Rx2, horn antenna, vertical polarization, LOS)

Fig. 5: Comparison of Bc_{75} between FC and EC (Rx1, horn antenna, vertical polarization, LOS)

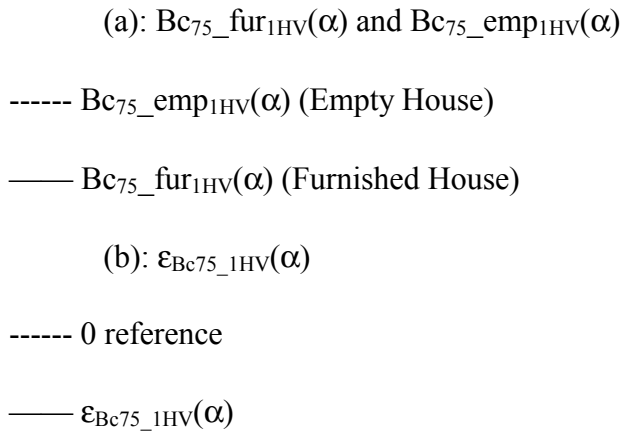


Fig. 6: Comparison of Nb_{paths} between FC and EC (Rx1, horn antenna, vertical polarization, LOS)

(a): $Nb_{paths_fur_{1HV}}(\alpha)$ and $Nb_{paths_emp_{1HV}}(\alpha)$

----- $Nb_{paths_emp_{1HV}}(\alpha)$ (Empty House)

—— $Nb_{paths_fur_{1HV}}(\alpha)$ (Furnished House)

(b): $\epsilon_{Nbpaths_1HV}(\alpha)$

----- 0 reference

—— $\epsilon_{Nbpaths_1HV}(\alpha)$

Table 1: 10th and 90th percentiles of the CDFs of $\epsilon_{C_iAP}(\alpha)$ for all propagation characteristics (PC)

(P10: probability (PC < P10) = 0.1)

Table 2: ϵ_{C_los} , ϵ_{C_nlos} , δ_{C_los} and δ_{C_nlos} values ($\epsilon_{(\%)} = 100 \cdot (10^{(0.1 \times \epsilon_{(dB)})} - 1)$).

Figure 1:



Figure 2:

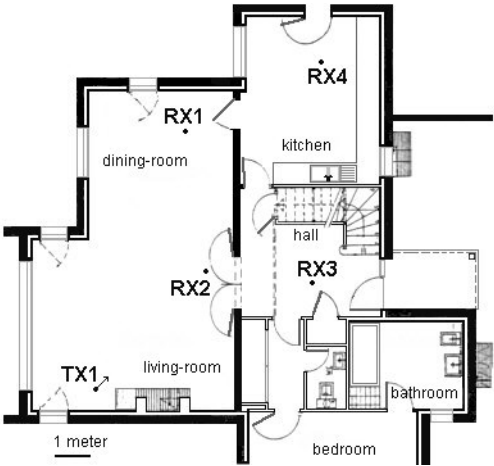


Figure 3:

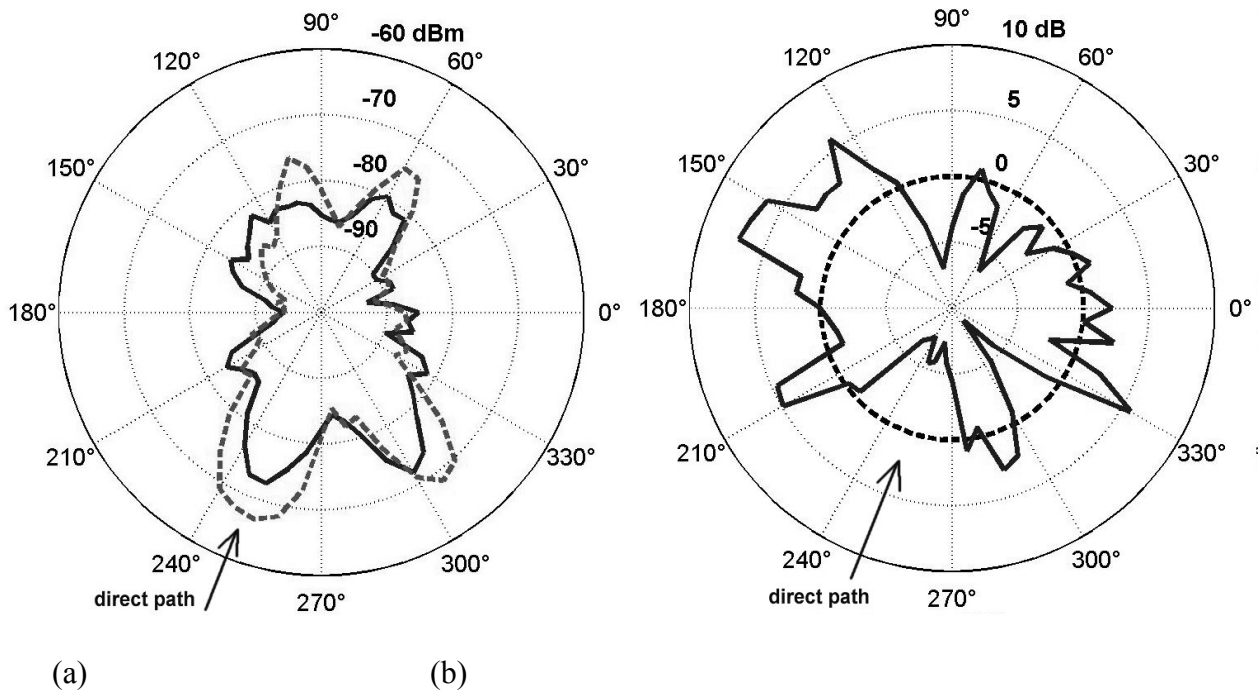


Figure 4:

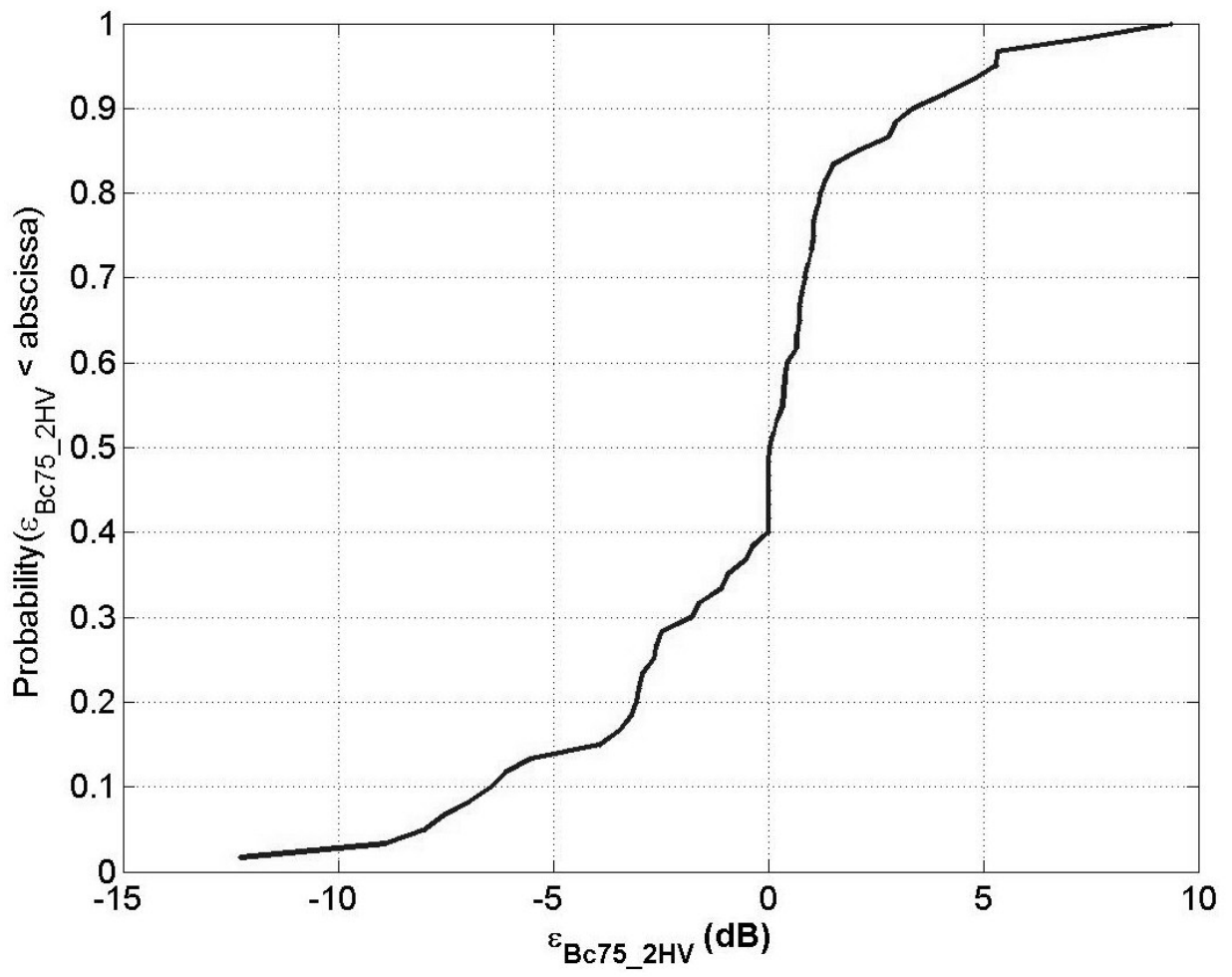


Figure 5:

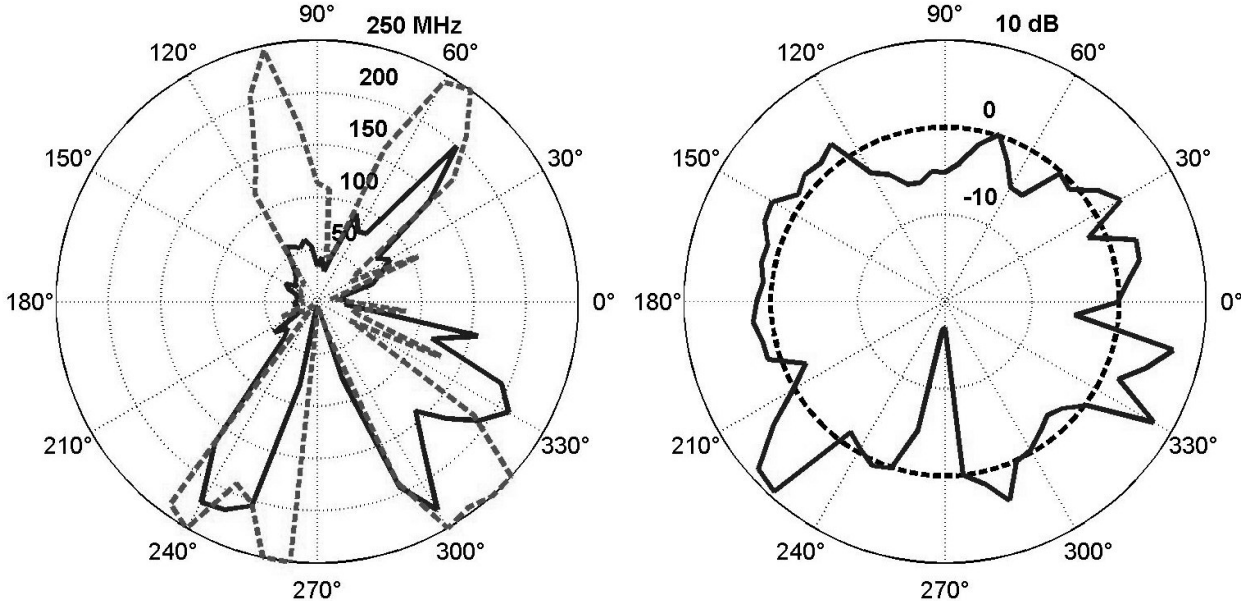


Figure 6:

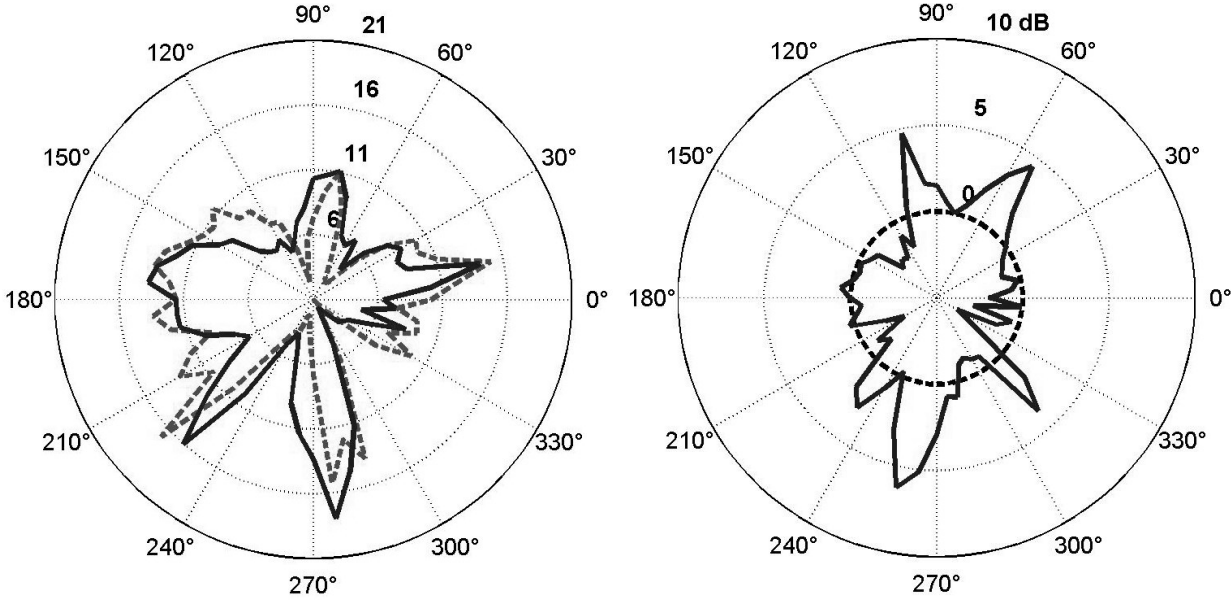


Table 1:

	LOS				NLOS			
	P10 (dB)	P10 (%)	P90 (dB)	P90 (%)	P10 (dB)	P10 (%)	P90 (dB)	P90 (%)
Pr	-1.78	-33.60	5.88	286.8	-3.44	-54.73	5.14	226.7
Bc ₇₅	-3.19	-51.98	5.61	263.9	-5.39	-71.08	4.00	151.0
DW ₉₀	-3.20	-52.12	2.40	73.62	-1.50	-29.19	2.98	98.38
Nb _{paths}	-2.54	-44.33	1.51	41.71	-0.65	-13.94	1.92	55.53

Table 2:

	ϵ_{los}		ϵ_{nlos}		δ_{los}		δ_{nlos}	
	(dB)	(%)	(dB)	(%)	(dB)	(%)	(dB)	(%)
Pr	-1.77	-33.4	-0.91	-19.0	2.75	88.28	2.81	91.04
Bc ₇₅	-0.598	-12.9	+0.653	+16.2	2.48	77.16	2.56	80.15
DW ₉₀	+0.092	+2.2	-0.679	-14.5	1.64	45.71	1.43	39.00
Nb _{paths}	+0.346	+8.3	-0.679	-14.5	1.26	33.54	1.05	27.28