# MEASUREMENTS AND SIMULATION OF MILLIMETER WAVE PROPAGATION AT 30 GHZ AND 60 GHZ IN INDOOR ENVIRONMENT

A. S. Polydorou and N. Uzunoglu

National Technical University of Athens
Department of Electrical & Computer Engineering
9 Heroon Polytechniou St., Athens 15773 – Greece
e-mail: amanda@esd.ntua.gr

**Abstract**

*The millimeter wave band appears to be a favourable choice for personal wireless communication systems for indoor environment, as it meets the requirements for sufficient bandwidth, small terminal dimensions and sporadic usage for commercial applications.*

*Measurements of millimeter wave propagation in both 30 GHz and 60 GHz bands in the NTUA premises, are presented in a comparative way. The topology of measurements coveres both a line-of-sight situation and also a case where a direct path between transmitter and receiver does not exist.*

*Both slow and fast fading characteristics of the received signal were studied and the measurements were modelled by the conventional Rician and Rayleigh distributions. Both frequency bands offer advantages for usage in in-house wireless communication systems. Although in 30 GHz band the coverage area is bigger than in 60 GHz (with the same transmitting power), frequency reuse is easier in 60 GHz band, because even if millimeter waves 'escape' through 'windows', the specific attenuation due to atmospheric oxygen (15 dB/km) at 60 GHz eliminates the interference between communication channels in neighbouring buildings.*

## 1. INTRODUCTION

Recently the application of millimeter waves for personal wireless telecommunication systems in indoor environment is of interest for commercial application. The sufficient bandwidth as well as the sparse usage for commercial applications make the millimeter waveband a favourable choice for present and future application especially in indoor environment.

Outdoor and indoor millimeter wave propagation has been studied in the past [1-5]. P. Smulders and A. Wagemans [1], have performed wideband measurements in indoor radiochannels operating in a 2 GHz frequency band centred around 58 GHz frequency. The results cover both line-of-sight and obstructed situations. Propagation measurements [2] of 60 GHz transmission between a hand - held transmitter and a receiver located at street lamp have been also performed in urban and rural locations. Fades 20 dB below the mean envelope level are observed 1% of the time.

In paper [3] the cochannel interference probability is evaluated for micro and picocellular systems considering the oxygen absorption at 60 GHz, while T. Manabe et all [4], have measured the complex refractive index at 60 GHz of soda-lime glass, which is commonly used as window glass, by means of a free space reflection method, using a vector-network analyser based scatterometer.

A 60 GHz channel sounding system is also presented [5], by which outdoor millimeter wave propagation measurements have been performed. In the same paper a statistical analysis of the measurements is presented.

On the other hand, measurements and simulation of received signals in room corridors and around corners at 21.6 GHz, 37.2 GHz and 59.6 GHz are presented in [7]. More recently the advances in millimeter wave indoor systems in Europe and Japan have been presented [10,11].

In this paper indoor propagation measurements and statistical processing at the frequency, bands of 30 GHz and 60 GHz are presented. The measurements configuration is also presented for both frequency bands.

The slow and fast fading characteristics of the millimeter wave channel have been studied. The measured fast and slow fading has been compared with well known statistical models, such as lognormal distribution for slow fading and Rician and Rayleigh distribution for fast fading. Both line of sight (L.O.S.) and corner situations have been covered.

## 2. EXPERIMENT METHODOLOGY

The topology of measurements covered both a line-of-sight situation and also a case where a direct path between transmitter and receiver did not exist so the received signal stemed from reflected or diffracted rays. Propagation measurements at the range of 30 and 60 GHz have been performed in the NTUA premises in a corridor of 3 m width, 4 m height and 30 m length.

The transmitter used a 25 dB ($10^o$ bandwidth) linear polarised horn antenna, powered by a 14 dBm 60 GHz tunable Gunn oscillator for the 60 GHz set-up and by a 1.5 dBm Gunn oscillator for the 30 GHz set-up. The transmitter chain was mounted on an small electrical carriage, that was moving with slow and stable velocity.

The receiver employed a same horn antenna, a Gunn diode negative resistance voltage controlled and mechanically tuned oscillator, with medium output power level and a passive cavity mixer with very good conversion loss of just 5.5 dB and 6 dB for the 60 and 30 GHz measurement set-up respectively.

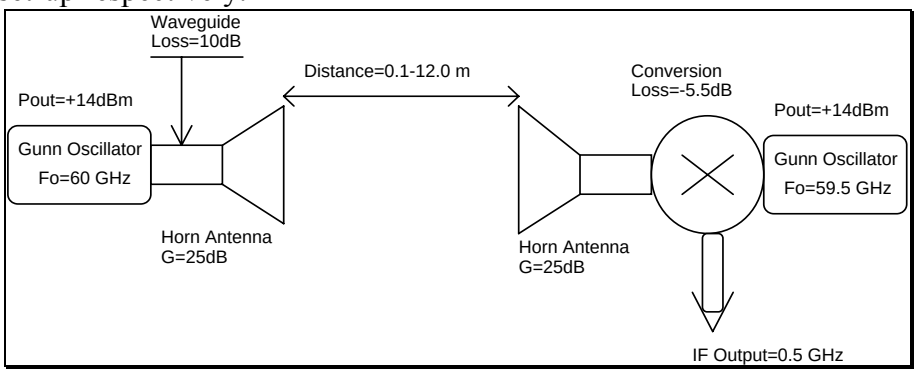



Figure 1. Experiment set-up for 60 GHz.

The IF down converted signal of the receiver's mixer was measured with a spectrum analyser HP-8592B. The spectrum analyser was linked and controlled through an HP-IB interface so as

all the measurements to be fully programmed. The measured IF power was registered in a file, while the transmitter was rolling away from the receiver with the stable velocity of the carriage.The experimental set-up for the 60 GHz measurement is shown in figure 1. Analogous was the set-up for the 30 GHz measurement set-up.

## 3. MEASUREMENTS - STATISTICAL PROCESS

The main goal in this section is to describe the wave propagation environment and derive a set of relevant parameters for the power budget inside the measured areas. So the channel is characterised in terms of

- propagation path loss
- slow fading statistics
- fast fading statistics.

A comparison is made between the two frequency bands in terms of the prescribed items.

### 3.1. Propagation Path Loss

The propagation model can be used to predict the average path loss between the receiver and the transmitter. A frequently used model indicates that the mean path loss increases exponentially with distance and is described as follows :

$$PL(d) = PL(do) + 10 \cdot n \cdot \log(d) \tag{1}$$

where PL(d) is the path loss at the straight line separation distance d between transmitter and receiver, do is a reference point that was chosen for the measurements to be equal to 20λ and PL(do) is the measured path loss at this point. The parameter n represents the power distance decay rate which indicates how path loss increases with distance. The free space propagation loss exponent is given by n=2.0. This model is an excellent candidate for use in environments where direct path and one or more reflection paths may occur.

The local mean signal level was obtained by averaging the recorded signal over a window of width 20λ. In that way the fast fading which was causing the received power to fluctuate rapidly was filtered out. The resultant signal represented the local average received signal and was fitted to equation [1]. In table [1] the parameters of the fitting regression lines which are the path loss at the reference point do, and the propagation loss exponent are confronted for both frequency bands.

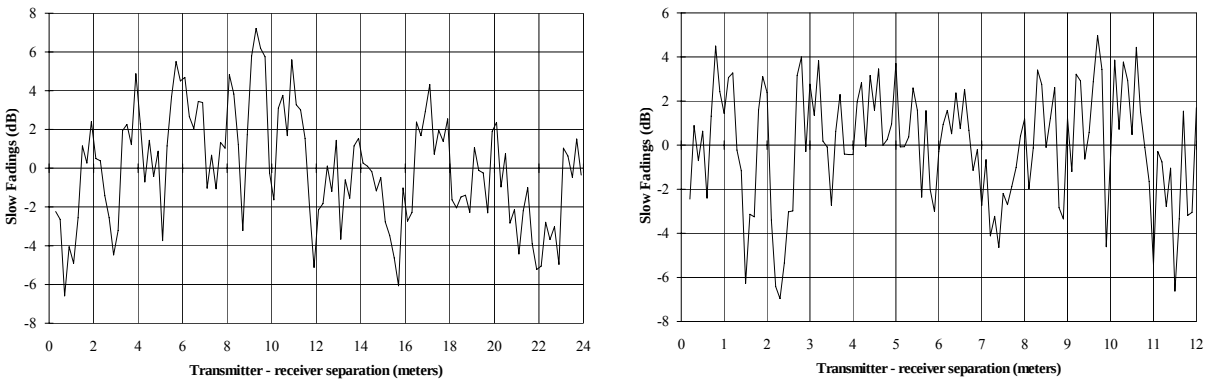
| | PL(20λ) | n |
|---|---|---|
| 30 GHz | 43.8 | 1.675 |
| 60 GHz | 48.5 | 1.962 |

Table [1]

As it can be deduced the best fitted lines to path loss curves correspond to a distance exponent between [1.6-2.0] for both frequency bands, which is below but comparable to the free space path loss. These results were expected, because the measurements were performed within a small distance from the transmitter, and cover only the L.O.S. case.

### 3.2. Slow Fading Characteristics

Having derived the propagation path-loss law, the slow fading characteristics of the measurements can be extracted, by subtracting the best fit pathloss regression estimate for each individual 20λ spaced averaged received signal values. Figure 2 shows typical plots of the slow fading for a 24 m data segment at 30 GHz, and a 12 m data segment at 60 GHz measurements respectively.

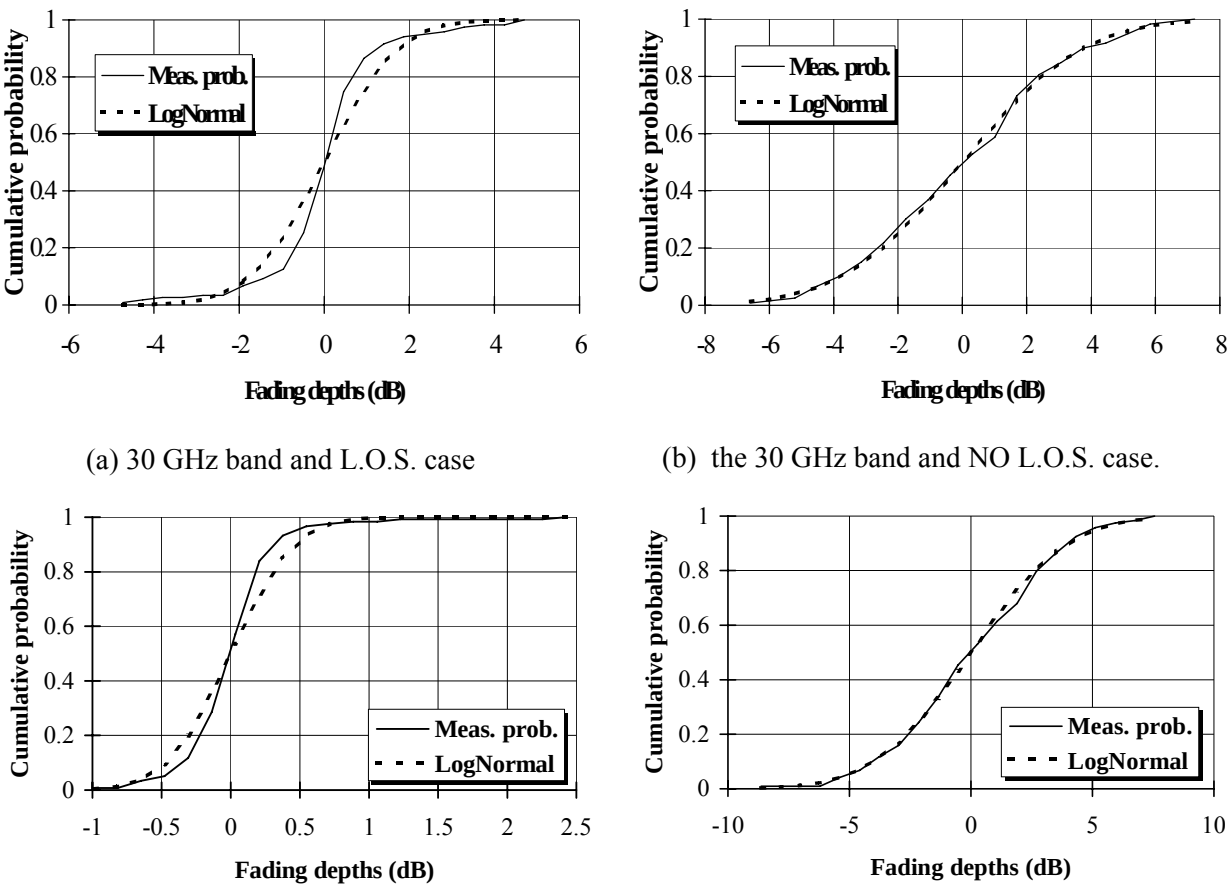



a) 30 GHz band b) 60 GHz band

Figure 2. Typical plot of the slow fading

The mean and the standard deviation of the measured data were calculated. Some typical values are shown in table [2] for both line of sight and obstructed cases, for the two frequency bands. As it was obvious the mean values are always zero, while the standard deviations vary widely. The minimum, maximum together with the mean values of the standard deviation for all the measured data sets are included in table [2].

After statistical process, the cumulative probability of the signal's slow fading is plotted and is compared to the log-normal statistical distribution as it is shown in figure 3. The statistical attitude of the slow fading signal's variations has been found to follow satisfactory the log normal distribution in both frequency bands, as it was expected. Subjecting the log-normal distribution to the Chi-square [12] goodness of fit test technique the distribution is confirmed at a high confidence level, as it is observed at table [2].




(a) 30 GHz band and L.O.S. case

(b) the 30 GHz band and NO L.O.S. case.

(c) 60 GHz band and L.O.S. case

(d) the 60 GHz band and NO L.O.S. case.

Figure 3. Cumulative distribution of the "local mean" compared with the fitted log-normal distribution

| | | Mean (dB) | Deviation (dB) | | | $X^2$ Log-normal |
|---|---|---|---|---|---|---|
| | | | MIN | MAX | AVERAGE | |
| 30 GHz | L.O.S. | 0 | 0.967 | 2.162 | 1.559 | 5.629 |
| | NO L.O.S. | 0 | 1.880 | 2.952 | 2.471 | 0.038 |
| 60 GHz | L.O.S. | 0 | 0.337 | 0.677 | 0.499 | 3.319 |
| | NO L.O.S. | 0 | 2.683 | 3.289 | 3.033 | 0.044 |

Table [2]

### 3.3. Fast Fading Characteristics

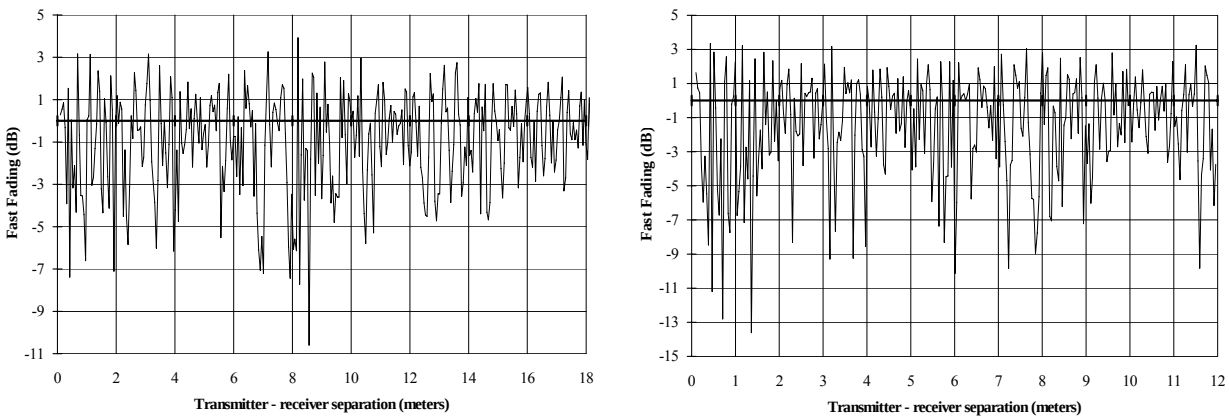
The fast fading characteristics describe the rapid change of the received signal's intensity over relative short distances due to incident waves. Each data segment is normalised with respect

to the local mean in order to remove the influence of shadow fading. This is done by evaluating the local average of the signal which is given in equation (2).

$$RMS(i) = \left[ \frac{1}{w} \cdot \sum_{i-w/2}^{i+w/2} meas(x_i)^2 \right]^{1/2} \quad (2)$$

where w represents the length of the window segments, and meas($x_i$) is the recorded measurement at distance $x_i$.

Typical normalised plots of fast fading are shown in figures 4 (a), (b). From these, it can be observed that the fast fades occur on a scale length of 1/3 m for the 30 GHz data and on a scale length of 1/6 m for the 60 GHz data.




a) 30 GHz band b) 60 GHz band

Figure 4. Typical plot of the fast fading

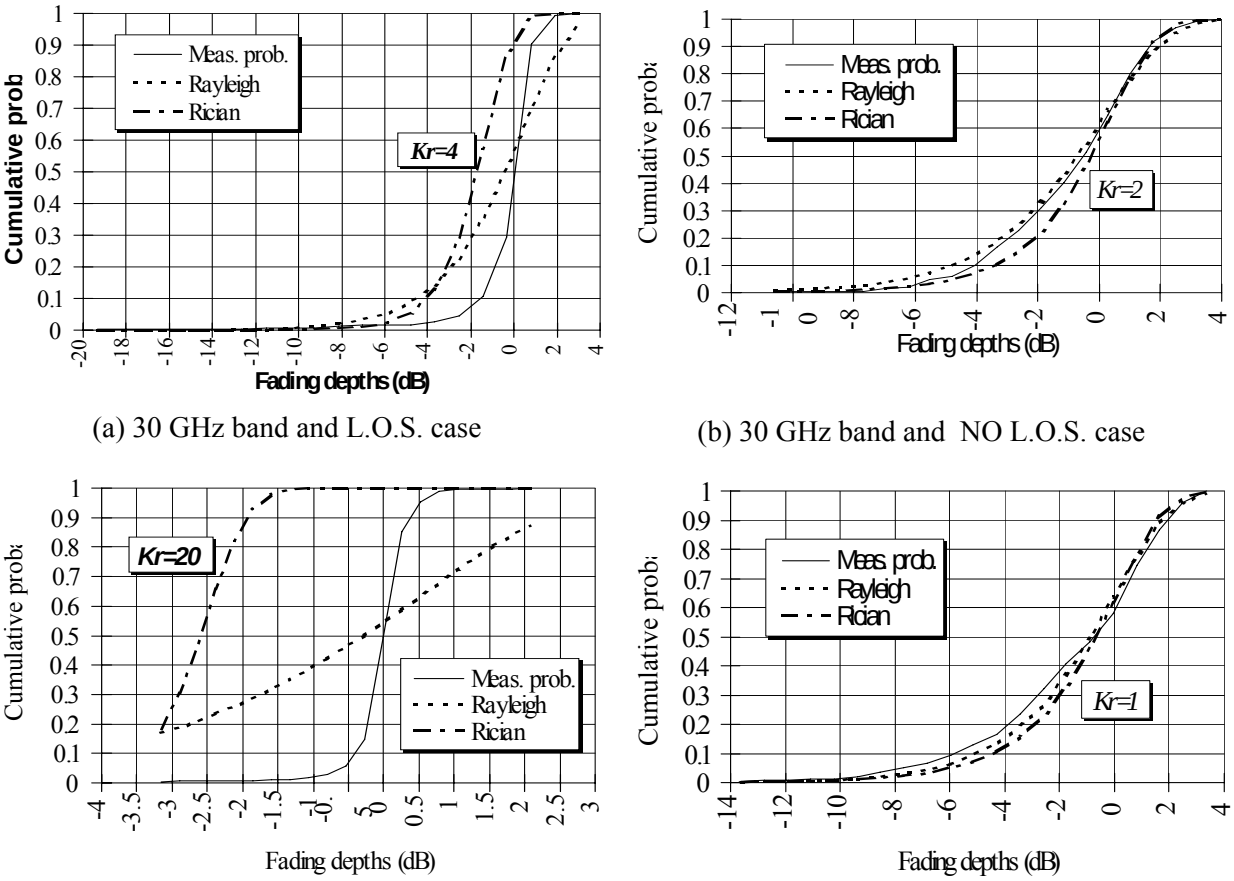
The mean and the standard deviation of fast fading were calculated and table [3] presents the results as previously. After statistical process the cumulative probability of the signal's fast fading is plotted and compared to the Rayleigh and Rician statistical distributions for line of sight and obstructed cases as it is shown in figure 5.

The fitting of the measurements to the above models was not perfect in the L.O.S measurement cases because the classical Rayleigh and Rician models are only justifiable where a fairly large number of scattering components exists. The results are shown in figure 3. For every measurement data the best Rician K factor was found and the $X^2$ (Chi-square) fitting test was performed to test the statistical relevance of a match between the measured and the hypothesis distribution. The results are shown in table [1].

| | | Mean (dB) | Deviation (dB) | $X^2$ Rayleigh | $X^2$ Rician | K Rician |
|---|---|---|---|---|---|---|
| **30 GHz** | ***L.O.S.*** | -0.110 | -6.553 | 1.610 | 1.797 | 4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | ***NO L.O.S.*** | -0.341 | -4.202 | 0.134 | 0.176 | 2 |
| **60 GHz** | ***L.O.S.*** | -0.019 | -10.090 | 3.137 | 6.738 | 20 |
| | ***NO L.O.S.*** | -0.583 | -3.139 | 0.152 | 0.274 | 1 |

Table [3]




(a) 30 GHz band and L.O.S. case

(b) 30 GHz band and NO L.O.S. case

(c) 60 GHz band and L.O.S. case

(d) 60 GHz band and NO L.O.S. case

Figure 5. Cumulative distribution of the "fast fading" compared with Rayleigh & Rician distribution

## 4. DETERMINISTIC MODEL FOR PREDICTION OF THE PROPAGATION LOSS BASED ON RAY-TRACING TECHNIQUES

A geometrical optics based model was also developped to predict the propagation characteristics. The Propagation Path Loss ($L_p$) was given from equation 3.

$$L_p = \frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi r_1}\right)\left|G_{direct} + \sum_{2}^{n} G_{r_i} R_i \frac{r_1}{r_i} \exp\left(-jk\left(r_i - r_1\right)\right)\right|^2 \tag{3}$$

$P_r$ /$P_t$ : was the total received / transmitted power,

$\lambda$ : the signal's wavelength,

$r_1$ : the distance between the two antennas,

$r_i$ : the distance covered by the i-th reflected component,

$G_{direct}$ : the antenna's gain product in the direction of the main ray,

$G_{ri}$: anten.gain product in the direction of the i reflected component and,

$R_i$ : the reflection coefficient in the plane where the reflection occurs and depends on the angle of incidence, the polarization and the relative dielectric constant of the material.

The ray tracing model was based on the building blueprint representation, taking into account the direct, transmitted and single - double reflected rays from walls, ceilings and floors. The results of the algorithm were successfully compaired with the results of the measurements that were made in the same premises and are shown in figure 4. Knife edge diffraction and geometric theory of diffraction were also used to explain and compaire results of diffraction by corners.

The study showed that ray tracing offers reliable approaches to the simulation of propagation conditions inside buildings opening the way to the development of a deterministic rather than a probabilistic approach to channel prediction in wireless indoor networks. The above approach is also particular interest not only as a tool to optimize coverage in a given room or building or to minimize interference and to optimize frequency reuse but also to give an inside towards exploiting the potential of adaptive antennas in the design of indoor communication systems.

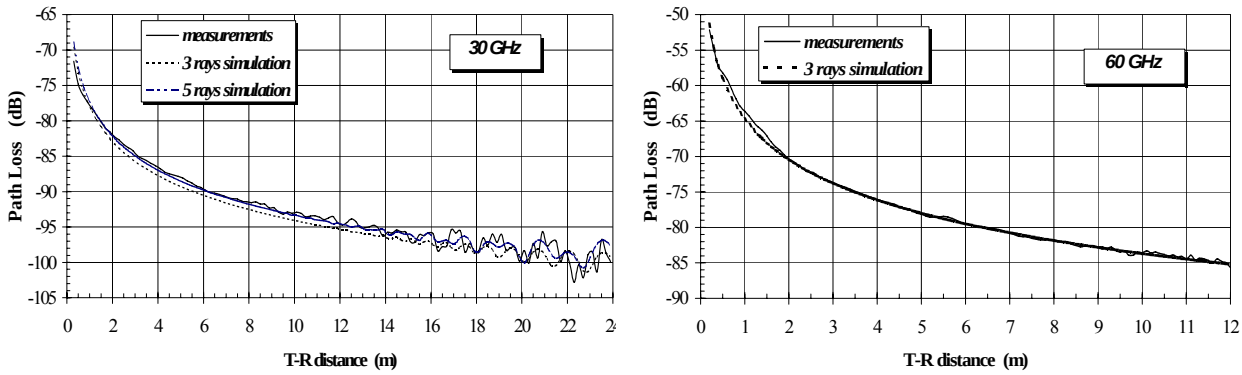



Figure 4. Results of the Ray-Tracing Model compared with the measured results.

## 5. CONCLUSIONS

The characteristics of the radiopropagation channel in the millimetre wave frequency spectrum of the 30 GHz and 60 GHz in indoor environment is accomplished. In the beginning the propagation mechanisms are controlled from the statistical point of view in order to make a macroscopic surveillance and a survey to the well known propagation tools.

Measurements were conducted in the corridors of the NTUA premises for two different location scenarios. First measurements that the existence of LOS between transmitter and receiver was imposed were performed and second measurements around corners where direct LOS was not possible and the received signal was mainly due to reflections from surrounding walls and diffraction from wedges were performed.

The path loss law was derived giving a propagation loss exponent of $n_{30}$=1.675 for the 30 GHz band and $n_{60}$=1.962 for the 60 GHz band.

Slow and fast fading statistics were derived in order to describe the wave propagation environment. The statistical attitude of the slow fading signal's variations has been found to follow satisfactory the log normal distribution in both frequency bands.

Finally the fast fading envelope was compared with both Rayleigh and Rician distributions. The fitting of the measurements to the above models was not perfect in the L.O.S measurement cases because the classical Rayleigh and Rician models are only justifiable where a fairly large number of scattering components exists.

It can be deduced that extensive measurements and processes have to be done in various indoor environments, so as to have more global view of the indoor propagation characteristics of the channel at the high microwave frequency bands 30-60 GHz. These will help the design of personal communications that would offer higher speed and higher capacity networks, able to confront the continuous growing demands for extra personal services.

Finally a deterministic approach of the propagation channel was realised using ray tracing models that are formed relying on the Geometrical Theory of Diffraction (G.T.D.), the Geometric Optics theory (G.O.), and the Physical Optics theory (P.O.). Thις approach is particular interest not only as a tool to optimise coverage in a given room or building or to minimise interference and to optimise frequency reuse but also to give an inside towards exploiting the potential of adaptive antennas in the design of indoor communication systems.

Ray tracing offers simple and reliable approaches to the study and simulation of propagation conditions inside rooms and buildings opening the way to the development of a deterministic rather than a probabilistic approach to channel prediction in wireless indoor networks.

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