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A Study of the Effect of Diffraction and Rough Surface Scattering Modeling on Ray Tracing Results in an Urban Environment at 60 GHz

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Abstract—**Channel characterization is an important step in the design of wireless communication systems. While channel sounding procedures are a useful method in determining channel behavior, they also require expensive and time consuming procedures and equipment. Ray tracing has been an important substitute for measurement in deterministic channel modeling and characterization of the wireless channel. Much has been done to improve the precision and efficiency of this method for lower frequency bands (generally below 5 GHz) over the years. Recently, with the worldwide announcement of a broad unlicensed band in the millimeter wave spectrum around 60 GHz, a great amount of attention has been paid to this frequency band, previously considered un-utilizable ([1, 2]). However some basic dissimilarity between the 60 GHz and UHF bands has brought about the need for modification of the methods previously used. In this paper the focus has been placed on two propagation mechanisms: diffraction and rough surface scattering, and the impact of each on over-all channel response predictions have been investigated.**

Keywords-millimeter wave propagation; ray tracing; wireless communication; urban channel characterization

I. INTRODUCTION

Various methods have been used by designers to model a wireless channel and predict the characteristics of its impulse response in different environments. While some methods use an empirical approach based on an enormous amount of measurements or simulations and in some cases the combination of these with physical laws of propagation, others use physical methods such as ray tracing based on physical optics combined with the uniform theory of diffraction (PO/UTD), to predict the propagation of radio-waves and establish a more or less deterministic description of the propagation environment, presenting a deeper, more thorough understanding of the factors that affect the channel response and the nature of their impact. The result of these models can further be used in the establishment of useful empirical models applicable to a vast range of environments, ready to be applied by system designers.

Along with the development of wireless cellular technology, extensive measurements and modeling have been carried out in the lower frequency bands (UHF). With the ever-growing demand for higher bit-rates, though, attention has been shifted to higher less

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constipated frequency bands, namely the millimeter wave band, specifically a newly unlicensed bandwidth around 60 GHz announced in a large part of the world [2]. The smaller wavelengths at these frequencies along with certain characteristics of propagation, including oxygen absorption, result in significantly different over-all channel responses for these frequencies in comparison to the much researched UHF and UWB bands; therefore necessitating the development of new models or modification of previous ones to meet the needs of a channel model for millimeter wave frequencies. Due to the drastic differences between propagation mechanisms in millimeter wave and UHF frequencies, the modification of predefined models used in the lower frequency range simply by changing the frequency of operation does not yield accurate results.

Here an attempt has been made to include the various distinctive characteristics of the 60 GHz frequency band in ray tracing simulations in order to obtain an appropriate and convenient model for the propagation channel in this range and further to determine the main mechanisms and characteristics that have the most impact on precision of these simulations. After a review of propagation mechanisms in the urban environment in the 60 GHz band, the approach used to model and simulate 60 GHz wave propagation will be introduced and an analysis of the results of ray tracing simulation will be presented. The conclusions and areas of further research are discussed in the last section.

II. PROPAGATION MECHANISMS IN THE MILLIMETER WAVE BAND

One of the most dominating phenomena in millimeter wave frequencies is gaseous absorption, specifically Oxygen absorption at 60 GHz. In the 60 GHz band, the concentration of resonance lines of oxygen causes a wide absorption peak around this frequency [3]. This peak, the amplitude of which is as great as 15 dB/km, though a significant factor in long distance links does not have a dominating effect in urban microcells. As we will see, the losses that wave fronts undergo through reflection off the rough surfaces and diffraction cause the path lengths of received components to be short, a few hundreds of meters at most, therefore oxygen absorption does not have as severe effect as it does in long terrestrial links. Rain and fog may also effect the attenuation that is strained upon waves propagating through the channel. A thorough discussion of these phenomena and formulation of losses is presented in [4] and [5].

A. Reflection and transmission

At lower frequencies, reflection from walls can be suitably described by calculating the Fresnel reflection and transmission coefficients. However, many of the surfaces encountered in an urban propagation channel cannot be assumed smooth at millimeter wavelengths; therefore the roughness of walls and other surfaces must be taken into account. In [6], measurements have been carried out for reflected and transmitted components of an incident wave for different surfaces with various angles of incidence. The paper has concluded that reflection from surfaces with roughness variation greater than 0.3 mm (6% of wavelength) is considerably attenuated and must be taken into consideration. With surfaces as rough as 1.7 mm (34% of wavelength), reflection is entirely attenuated – with excess attenuation as great as 30 dB – unless for small grazing angles. Here we have analyzed the over-all effect of roughness on channel response using the formulas provided in [6] and [7] for modeling reflection.

For a smooth surface, the reflection coefficient can be calculated using (1) and (2) for parallel and perpendicular reflections respectively. These coefficients are known as Fresnel reflection coefficients. In reflection from rough surfaces, however, these coefficients overestimate the reflected power since some of the incident power is scattered in various directions. In these equations, ε_1 and ε_2 are the permittivity of the incident and reflecting mediums respectively, and φ is the angle of incidence.

$$r_{\parallel} = \frac{\varepsilon_2 \cos\varphi - \sqrt{\varepsilon_2\varepsilon_1 - \varepsilon_1^{\,2}\sin^2\varphi}}{\varepsilon_2 \cos\varphi + \sqrt{\varepsilon_2\varepsilon_1 - \varepsilon_1^{\,2}\sin^2\varphi}} \tag{1}$$

$$r_{\perp} = \frac{\cos\varphi - \sqrt{\varepsilon_2/\varepsilon_1 - \sin^2\varphi}}{\cos\varphi + \sqrt{\varepsilon_2/\varepsilon_1 - \sin^2\varphi}} \tag{2}$$

A measure for the roughness of a surface is the standard deviation of its height, σ. But other than roughness height, the correlation length of surface height, l_c, is also a determining factor. This parameter is defined as the shortest distance between two points with zero cross correlation of height. For rough surfaces, the Fresnel coefficient is multiplied by a roughness correction factor, ρ_s as shown in (3), (4) and (5), to give the overall amplitude of the reflected component[6, 7].

$$R = \rho_s R_F \tag{3}$$

$$\rho_s = \max[\exp(-\frac{1}{2}g^2), 0.15] \tag{4}$$

$$g = \frac{4\pi\sigma}{\lambda}\cos(\phi) \tag{5}$$

For very rough surfaces ($\sigma \sim \lambda$, $l_c < \lambda$), however, it has been shown in [9] that no specular component is emitted from the surface, and the incoming power is scattered in all directions.

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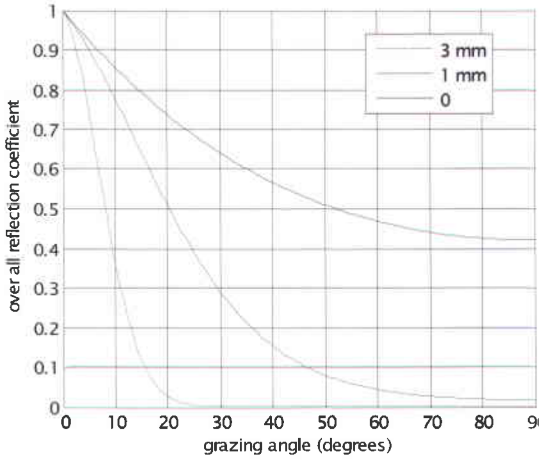

Figure 1. Overall reflection coefficient as a function of grazing angle

To demonstrate the effect of the angle of incidence (or grazing angle) on excess attenuation due to roughness (ρ_s), the over-all reflection coefficient has been plotted in Fig. 1 as a function of grazing angle (90 - ϕ) for perpendicular reflection from smooth, rough and very rough surfaces with roughness heights of 0, 1, and 3 mm (or 0, 20, and 60% of wavelength) respectively and permittivity of 6. It is obvious that roughness is mainly effective in greater grazing angles, and small grazing angles remain unaffected by rough surface scattering. This can be an important factor when considering reflections along long streets where very low grazing angles are common.

Some common building materials in an urban environment have been listed in Table 1 along with their surface height deviation as reported in [6].

Transmission through walls may well be neglected at millimeter wave frequencies due to the high attenuation that waves undergo while passing through dielectric walls. This higher attenuation is mainly due to the increase in frequency, as can be seen from (6) and (7) even if the electromagnetic properties of building materials does not differ considerably from that of lower frequencies, the exponential attenuation constant, α, increases linearly with the increase in frequency.

TABLE I. ROUGHNESS HEIGHT OF SOME COMMON URBAN BUILDING MATERIALS IN MILLIMETERS

Granite	0.6
Aerated concrete	0.2
Brick	micro 0.3, macro 2
Tiles	0.1
Plasterwork	1.2
Polyfoam	0.4
Rockwool	0.9
Wood	0.2
Rough glass	0.3

$$k = \omega\sqrt{\mu(\varepsilon' - j\varepsilon'')} = \beta - j\alpha \qquad (6)$$

$$\alpha = \omega\,\mathrm{Im}(-\sqrt{\mu(\varepsilon' - j\varepsilon'')}) \qquad (7)$$

Considering the exponential evanescence of waves with an exponent of α, such an increase in α will result in severe attenuation of transmitted components through a wall of constant thickness compared with lower frequencies.

B. *Diffraction*

In a similar geometry (Fig. 2), diffracted waves with smaller wavelengths undergo higher attenuation. This can be seen from the approximate formula of excess diffraction loss discussed in [10]:

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \qquad (8)$$

$$L_{ex} \approx -20\log\frac{0.225}{v} \qquad (9)$$

According to this equation, excess diffraction loss at 60 GHz is 17 dB more than what it is at 1 GHz in a similar geometry. It may be concluded from this hypothesis that diffraction has a less significant effect at the high frequencies dealt with here. As diffraction modeling is the time consuming part of ray tracing simulations, the possibility of using faster though less accurate methods for diffraction modeling may lead to faster more convenient tools for channel modeling.

III. RAY TRACING MODEL AND SIMULATION SCENARIO

A 1000m×440m area of the city of Ottawa has been considered for this simulation. The approximate locations of buildings have been read off a bird's eye view map of the city and used as a typical urban environment. The base antenna is placed within one street and the signal received in nearby streets has been monitored. The walls are assumed to be made of concrete with relative permittivity of 7 and the ground's permittivity is assumed to be 15. A Conductivity of 0.2 and 0.05 is considered for the walls and ground respectively[8].

An isotropic antenna has been considered in this scenario with a height of 3.1 m and the height of surrounding buildings is thought to be much greater than the transmitter and receiver antennas so that diffraction over buildings may be neglected and 2.5D ray tracing can be considered as an acceptable

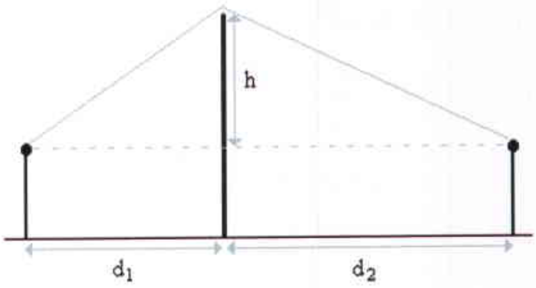

Figure 2. Diffraction geometry

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approximation. Receiver heights have been assumed to be about 2.8 m. A total of 3600 rays with uniform angular spacing are emitted from the transmitter and traced through the city until they either leave the map or die down to a level corresponding to 10 km of propagation. Rays that hit building corners are assumed to be diffracted in all directions with diffraction loss of each direction calculated using the Uniform Theory of Diffraction [11]. In other words, the building corner is modelled as a new origin of radiation emitting up to 120 new rays with a uniform angular spacing of 3 degrees. The angular spacing of diffracted rays cannot be chosen very small seeing as it has an exponential effect on program run time. Rays are traced in two dimensions and for each path connecting the transmitter to a receiving point, the corresponding ground-reflected path is added to the received components thus turning the simulation into a 2.5 D simulation.

Here the focus has been placed on the effect of certain mechanisms including diffraction and rough surface scattering on reception and impulse response characteristics. Various simulations with different assumptions of surface roughness (between 0.1 mm to 1 cm roughness height) have been carried out for comparison. Equations 1-3 have been used to calculate roughness factor for reflections and the Uniform Theory of Diffraction based on diffraction from a perfect conducting wedge has been used for diffraction modelling.

All of these simulations have been run with the assumption of clear weather with standard water vapour content (7.5 g/m^3) and zero liquid water content (no fog or rain).

Signal levels have been calculated in 10 m steps inside the area surrounding the transmitting antenna, placed at [x, y] = [217, 270] meters. By changing the roughness height variance of wall surfaces, the size and shape of the reception area (that may be considered a cell in planning a cellular network) is seen to change considerably. This effect will be discussed more thoroughly in the next section.

Diffraction effect has been analyzed by calculating the percentage of received power conveyed via diffracted components and the correlation of this parameter with received power, thus providing a quantitative measure for the impact of diffraction on the accuracy of simulation results. The result of this analysis has also been discussed in the next section.

IV. ANALYSIS OF THE RESULTS

Fig. 3.a, 3.b and 3.c show received power in the cases of smooth, rough ($\sigma = 1$ mm, $\sigma/\lambda = 0.2$), and very rough ($\sigma = 5$ mm, $\sigma/\lambda = 1$) wall surfaces. It can be seen that in the case of rough or very rough surfaces acceptable signal strength is limited to LOS areas, namely, within the street containing the transmitter. As

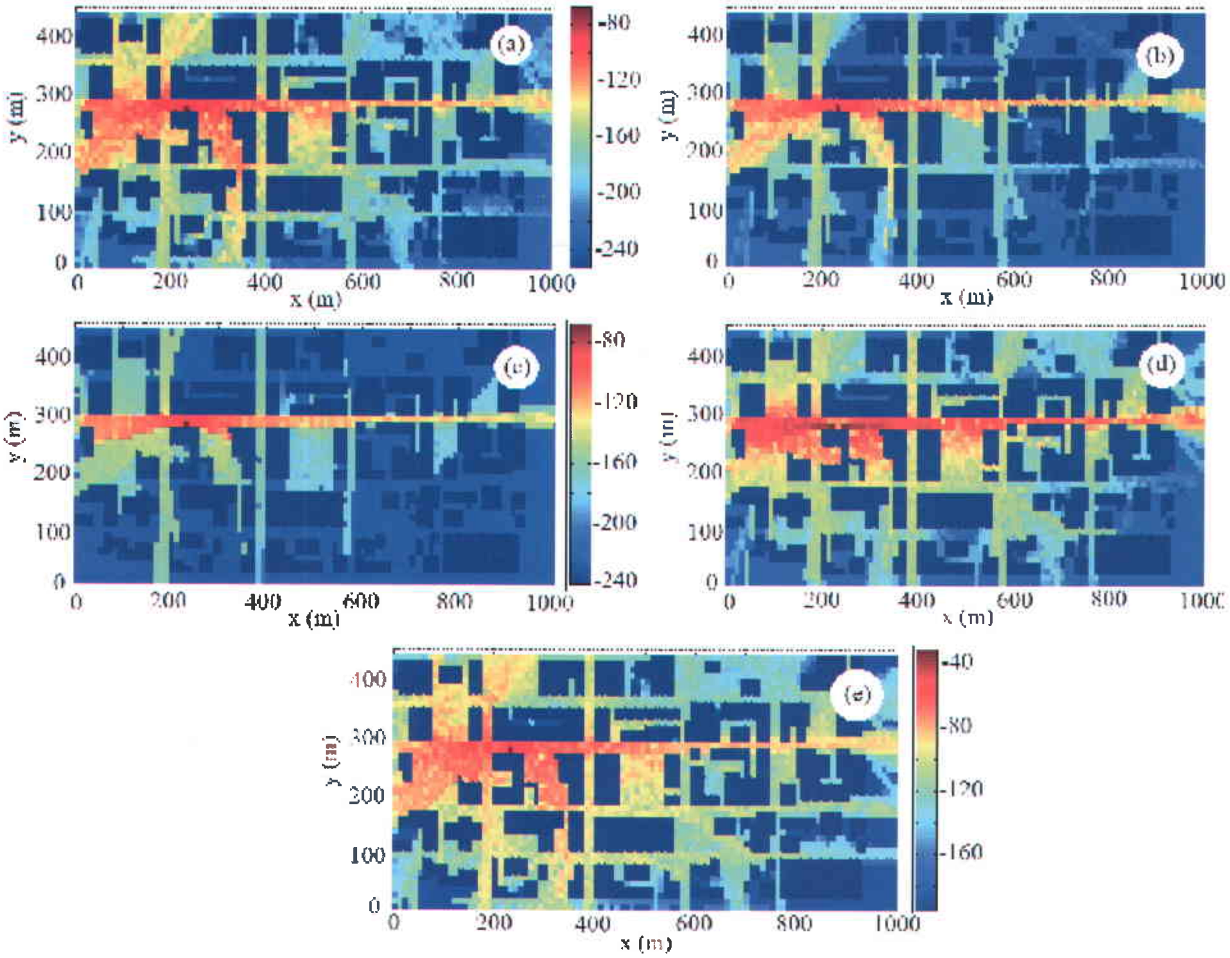

Figure 3. Received power on a bird's eye view of the city in the cases of (a) smooth, (b) rough and (c) very rough wall surfaces with an omni-directional transmitter, (d) with smooth surfaces and a directive transmitting antenna, at 60 GHz, and (e) with smooth walls and an omni-directional transmitter at 920 MHz.

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the surface height variation of few millimeters is common in urban environments (e.g. concrete, cement, etc) signal reception outside the street containing the base station is not reliable in a general assumption.

Fig. 3.e shows the results of ray tracing assuming smooth wall surfaces at a lower frequency of 920 MHz for comparison. It is observed that at this frequency, propagation of energy into NLOS areas is considerably high and even far away streets receive power with less than 20 dB difference from the street containing the transmitter. The restriction of power to LOS areas or the same street at 60 GHz makes the problem of network planning somewhat different from lower frequencies.

Though many surfaces in the urban environment are rough enough to keep the signal from penetrating to NLOS points, the presence of windows or other smooth surfaces like polished stone, granite, etc may reflect considerable energy into neighboring streets. These phenomena impose great uncertainty in predicting signal strength and effective planning of wireless cellular systems; and precise prediction of reception points will require exact knowledge of roughness characteristics of all surfaces in the area, which is difficult to obtain for each and every scenario.

This amount of influence of surface roughness on channel predictions is due to the small wavelength at 60 GHz (5 mm) which is in the order of the roughness of many surfaces encountered in reality. That is why this phenomenon has not been an issue at the much investigated lower frequencies and therefore is one of the main problems that must be addressed in millimetre wave ray tracing and modelling.

One proposition is the use of directive antennas to keep the signal inside the main street and prevent it from leaking into neighbouring cells. The result of using a directive antenna with 10 dBi gain (Fig. 4) at the transmitter is depicted in Fig. 3.d.

One point that must be noted is that though surface roughness has a great influence on received power in NLOS cases; it does not have such an influence at LOS points. Not only is the LOS component considerably strong at these points, but also due to the small grazing angles of reflected paths, the roughness factor that the reflection coefficient is multiplied by is close to one (see (3), (4) and (5)) and therefore surface roughness does not greatly impact the power of reflected components.

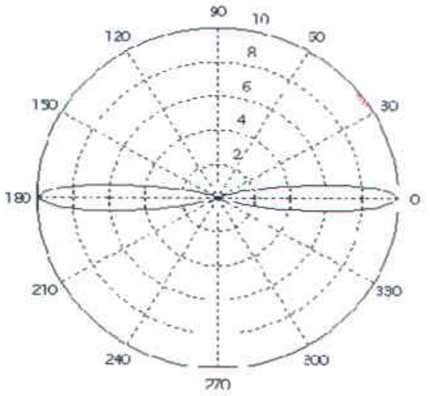

Figure 4. **Pattern of directive transmitting antenna**

A. Impact of diffraction

The impact of including diffraction in the simulation has been measured in a more or less quantitative manner in order to obtain a more practical insight into the importance of diffraction in these applications.

Fig. 5 shows the influence of diffracted components at various signal levels. The ratio of diffracted components received at each point to the total received power at that point has been considered as a measure for the impact of diffraction at that point. Diffraction ratios higher than 0.2 (where over 20% of received signal is a result of diffraction) have been considered high enough to make diffraction modelling noteworthy. As it can be seen in these figures, high diffraction proportions occur mostly at points with low signal power, unlikely to be picked up by most common receivers. For instance, in all cases, less than 10% of points with path losses less than 130 dB contain more than 20% diffracted components. It may be worth mentioning that a 20% error results in 1 dB difference in the predicted signal levels, which can easily be neglected. In other words, dismissing diffracted components altogether would result in less than 1 dBi error in received power estimations for points with less than 20% of the received power containing diffracted components.

Assuming receivers with 60 dB dynamic range are used, points with path loss between –120 dBi and – 60 dBi can be considered as reception points. From Fig. 5.a and Fig. 5.b it can be seen that less than 2% of these points are noticeably affected by diffraction; therefore deeming diffraction modelling unnecessary.

The same simulations have been carried out at a lower frequency of 920 MHz and the results are shown for comparison in Fig. 5.c. It is clear from this figure that at this low frequency, even points with low path loss may receive a considerable contribution from diffracted components. Here over 40% of reception points with the highest amount of received power have a considerable contribution from diffracted components, and almost 80% of the points within the 60 dB dynamic range are noticeably affected by diffraction. The spatial distribution of these points can be seen in Fig. 3.e. Contrary to the 60 GHz scenario, here high power reception is present even in far away NLOS regions, which shows the higher capability of NLOS phenomena, namely reflection and diffraction, for power transmission.

Therefore it can be concluded that the higher excess loss due to diffraction effectively diminishes the impact of diffraction on received power at frequencies as high as 60 GHz.

It may be added here that the formula used in modelling diffraction tends to over-estimate the diffracted component's power level in the case of an uneven dielectric edge.

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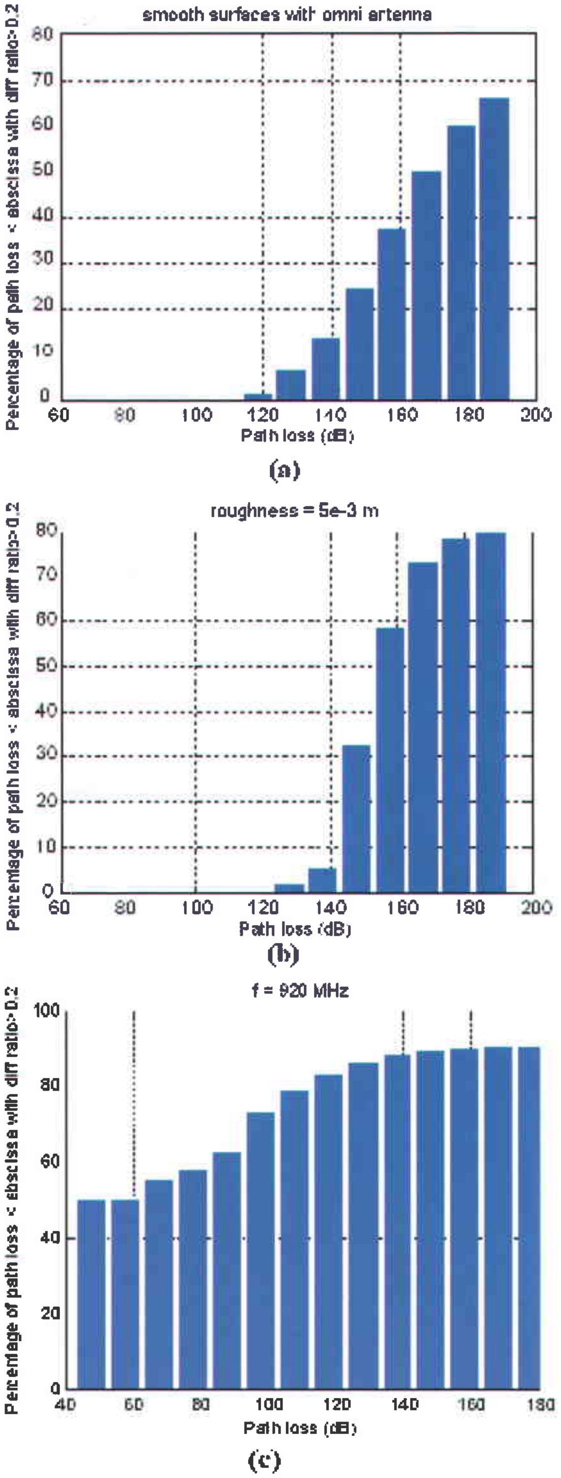

(a)

(b)

(c)

Figure 5. Variation of the influence of diffraction with received power

V. CONCLUSION

Results of 2.5D ray tracing at 60 GHz were obtained in a typical urban scenario and the effect of the roughness of building surfaces on the reception area was examined. Roughness of the walls was seen to have a significant influence on the received power mainly in the NLOS zone, where a roughness height of one or a few millimeters effectively constrains reception to the street containing the base station. Therefore it is predicted that modelling rough surface reflection loss and exact knowledge of the roughness parameters of walls is essential in obtaining reliable results from ray tracing. Using a directive antenna with 10 dBi gain at the transmitter also showed lower signal levels outside the main street.

The impact of diffraction was investigated by calculating the ratio of power conveyed via diffracted components to total power at receiver points, and the results showed that points were diffracted components are a considerable fraction of the received power are mostly points with power levels unlikely to be picked up by receivers, and precise modelling of diffraction is not crucial in power level predictions in mm-waves. Although it may be added that in interference calculation, which is also an important part of cellular planning, diffracted signals are not expendable and must be considered.

Over all, seeing as power transmission to NLOS points is mainly done through consecutive reflections and diffraction, the lower impact of these two mechanisms at 60 GHz results in low NLOS reception. In fact, at 60 GHz only LOS points can be expected to have sufficient and reliable reception.

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