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A Novel Geometrical Height Gain Model for Line-of-Sight Urban Micro Cells Below 6 GHz

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Abstract—This paper presents a novel height gain model applicable to line-of-sight urban micro cell scenarios and frequencies below 6 GHz. The model is knife-edge diffraction-based, and it is founded on simple geometrical and physical relationships. Typical system level simulator parameters are used as inputs to the model, where the only variable is outdoor-to-indoor penetration loss as it can vary depending on the external composition of the target building. The model is validated against two independently-obtained sets of measurements taken at different locations in China and Denmark. The model presents an average root-mean-square error accuracy of 6-7 dB, about 1-3 dB better than current existing models.

I. INTRODUCTION

Micro cells are outdoor low power base stations (BS) intended to cover small areas up to a few hundred meters, where macro cells do not provide enough network coverage, or crowded areas where additional capacity is needed. A lot of work has been already reported in the literature concerning to propagation modeling for this type of cells. However, most of the empirical works and models consider only the horizontal domain, focusing on the analysis of the path loss between the micro BS antenna and the user equipment (UE), typically located at street level [1]. In order to improve the characterization of the urban micro cell scenario, the vertical domain needs to be examined as well. This is a major issue, especially when addressing outdoor-to-indoor propagation, as radio signal penetration inside buildings may be very dependent on the incident angle [2], which can result in higher floors (with smaller grazing angles) experiencing much more reduced coverage than lower floors located at the approximate height of the BS (closer to normal incident angles).

None of the most widely used outdoor-to-indoor path loss models, proposed by the 3GPP and ITU-R standardization bodies [3, 4], compensate for the gains (or losses) in the elevation domain further than the natural correction given by the variable 3D distance between BS and UE. This is fine for typical hotspot micro cell scenarios such as squares or shopping areas, typically located around the street level.

However, new use cases have arisen, such as the high-rise office building scenarios [5], where uptilted micro cells are used to provide coverage inside large office buildings as an alternative to the expensive deployment of indoor small cells. It is clear that, in this case, a deeper understanding and better modeling of the elevation domain is crucial in order to properly characterize these new scenarios.

In the past, the elevation domain was addressed by compensating the path loss predicted at street level for upper floors, by applying height gain (HG) factors, in the range from 1.8-4 dB/floor for macro cell scenarios [6, 7], and 1.1-1.6 dB/floor for micro cell scenarios. This linear modeling approach is able to capture the average behavior of the elevation domain. However, it is not very accurate, as the experienced HG can be very different from scenario to scenario due to the variant BS illumination conditions, propagation mechanisms [8], building types and materials, and indoor UE locations. More accurate modeling considering the different variables in the elevation domain is, therefore, still needed. A first approach was recently reported in [9], where an empirical HG model considering the vertical grazing angle dependence was presented.

This paper complements the previous work by presenting a geometrical approach to HG modeling for line-of-sight (LOS) micro cell scenarios. A simple model based on knife-edge diffraction considering both vertical and horizontal domains is derived from basic physical observations. The model, able to capture situations that the other existing models do not differentiate, is tested and validated against two different and independently obtained extensive sets of measurements, considering a wide range of frequencies, micro BS antenna heights, building heights and cell ranges.

The rest of the paper is organized as follows: Section II introduces the proposed HG model based on knife-edge diffraction. Section III presents the measurement-based model validation in which the model is tested for different geometrical combinations and frequencies, and compared with existing models. And, finally, Section IV concludes the paper.

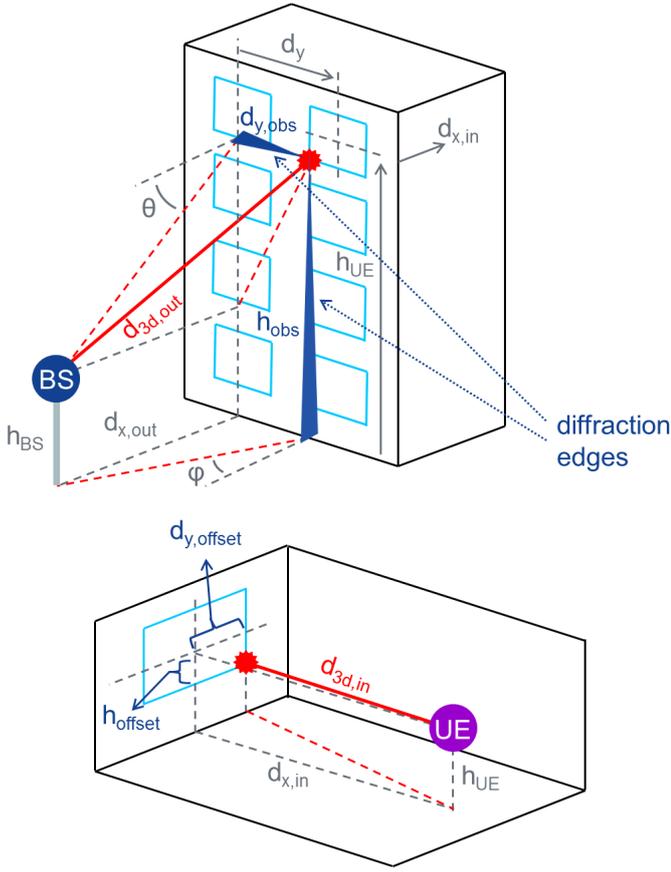


Fig. 1. Overview of the scenario geometry.

II. PROPOSED HEIGHT GAIN MODEL

A. Geometrical and Physical Foundation

Radio signals penetrate the external facade of the buildings through low-attenuation openings (e.g. windows) [10]. Based on this observation, one can understand that the signal propagates from the BS to the window closer to the UE, penetrates through it, and propagates further into the building until reaching the UE. This situation is illustrated in Fig. 1, where the BS is at a height of h_{BS} and at a perpendicular distance to the building of $d_{x,out}$. The signal enters the considered compartment/room at a grazing angle (normal referenced) of ϕ , measured in the horizontal plane, and θ in the elevation plane. The user in the compartment is located at a height of h_{UE} , at indoor distance $d_{x,in}$ and horizontal distance d_y from the BS.

The model assumes that, since propagation at low frequencies is mainly driven by diffraction, the outdoor signal is not only attenuated by the glass, but also diffracted at the frame of the window, and more in particular, at the corner of the frame with shortest distance to the BS. This diffraction is dependent on the incident angle over the facade of the building. The model splits this diffraction into two components: one for the horizontal domain (dependent on ϕ) responsible for azimuth correction, and one for the vertical domain (dependent on θ) which is key in HG

compensation. These two components are approximated as knife-edge diffracted contributions based on the standard geometry of the scenario. For further clarification, both the horizontal and vertical diffraction edges are illustrated in Fig. 1.

B. Model Formulation

Following the physical and geometrical foundation, the model splits the overall path loss (PL) between the BS and the user in three components: outdoor (PL_{out}), outdoor-to-indoor ($PL_{out-to-in}$) and indoor (PL_{in}), as indicated in (1).

$$PL = PL_{out} + PL_{out-to-in} + PL_{in} \quad [\text{dB}] \quad (1)$$

As the target buildings are in LOS, the outdoor path loss, in (2), is assumed to be free space ($FSPL$) [11], computed over the particular carrier frequency of operation (f) and the 3D distance between the BS and the closest corner of the window closer to the UE ($d_{3d,out}$), as previously mentioned.

$$PL_{out} = FSPL(f, d_{3d,out}) \quad [\text{dB}] \quad (2)$$

The outdoor-to-indoor path loss, in (3), is separated into two components: a constant part resembling the attenuation experienced while penetrating into the building at normal incidence ($PL_{wall,ext}$), and a variable diffraction-based part accounting for the geometrical outdoor-to-indoor HG dynamics (L_{diff}).

$$PL_{out-to-in} = PL_{wall,ext} + L_{diff} \quad [\text{dB}] \quad (3)$$

The indoor PL, in (4), is computed as a linear attenuation factor of 0.5 dB/m multiplied with the indoor 3D distance from the window corner to the UE ($d_{3d,in}$), exactly as proposed in the current standardized 3GPP and ITU-R models [3, 4].

$$PL_{in} = 0.5 \cdot d_{3d,in} \quad [\text{dB}] \quad (4)$$

The key part of the model is the diffraction component and, as mentioned previously, it drives the dynamics of the model in both the vertical and the horizontal domains. It is calculated in (5), as the average between the estimated diffraction in elevation ($L_{diff,elev}$) and the estimated diffraction in azimuth ($L_{diff,azim}$). It should be noted that the average is necessary, otherwise the model will be accounting for a double diffraction.

$$L_{diff} = 0.5 \cdot L_{diff,elev} + 0.5 \cdot L_{diff,azim} \quad [\text{dB}] \quad (5)$$

Each one of the diffraction components is calculated independently as the knife-edge diffraction loss ($KEDL$) experienced at each of the planes. The vertical component, in (6), is computed on the xz plane over the diffraction edge with height h_{obs} situated on the xz plane at distance $d_{x,out}$ from the BS, and $d_{x,in}$ from the UE. In this plane, the BS and the UE are located at h_{BS} height, respectively. Similarly, the horizontal component, in (7), is computed on the xy plane over the diffraction edge with distance $d_{y,obs}$. In this plane, the BS is located at the origin and the UE at distance d_y .

$$L_{diff,elev} = KEDL(f, h_{BS}, h_{UE}, h_{obs}, d_{x,out}, d_{x,in}) \quad (6)$$

$$L_{diff,azim} = KEDL(f, 0, d_y, d_{y,obs}, d_{x,out}, d_{x,in}) \quad (7)$$

The model assumes that the UE is located in the direction normal to a window. Under this assumption, it is possible to define the position of the window corners, and subsequently of the diffraction edges, relative to the UE location as indicated in (8) and (9). The vertical (h_{offset}) and horizontal ($d_{y,offset}$) offsets account for the window size.

$$h_{obs} = h_{UE} - h_{offset} \quad [\text{m}] \quad (8)$$

$$d_{y,obs} = d_y - d_{y,offset} \quad [\text{m}] \quad (9)$$

By assuming an average floor height of 3 m, and a window size of 1.5x1.5 m; if the UE is situated 1.5 m above the floor level, then $h_{offset} = d_{y,offset} = 0.75$ m. These are the values used later for the model validation, and have been proved to be a good selection. Choosing very different offsets would deviate from reality and could bias the model predictions, especially if the selected offsets are very small, which would result in a clear overestimation of the diffraction loss.

As diffraction is frequency-dependent, the model automatically adjusts to the selected carrier frequency without any further term. The described knife-edge diffraction losses in (6) and (7) can be computed with standard electromagnetic calculations. In this case, the Lee approximation to the Fresnel integrals is used [12]. The mathematical formulation is given in Appendix A.

C. Model Dynamics

The main novelty of this model is the automatic compensation of the outdoor-to-indoor path loss in the vertical and horizontal domains based on knife-edge diffraction. Fig. 2 presents an example of the dynamics predicted by the model through the diffraction component L_{diff} . The example considers the scenario described in Fig. 2.a, with a 30-storey building (90 m height), and two BSs, one at $d_{x,out} = 50$ m, and the other one closer to the building at $d_{x,out} = 10$ m, both at $h_{BS} = 20$ m. 3 different indoor locations are explored inside the building: P1 with $d_y = 0$ m and $d_{x,in} = 2$ m, P2 with $d_y = 20$ m and $d_{x,in} = 2$ m, and P3 with $d_y = 20$ m and $d_{x,in} = 20$ m.

Fig. 2.b, illustrates the diffraction term predictions for the different indoor locations. As P1 is located in the direction of normal incidence and very close to the external facade of the building, it experiences lower losses compared to P2 and P3. At the exact same height of the BS, 20 m, this loss is even 0 dB, as at this height the line-of-sight between BS and UE is not obstructed, and the signal would be only impacted by the attenuation of the window itself and not by any diffraction. P2 exhibits higher loss than P1 as it is impacted by the grazing angle in the horizontal domain. As P3 is located in a deeper indoor location compared with P2, it experiences an even higher loss. By comparing the predictions for the two different BSs, it is possible to observe how for the farthest one (50 m), a lower loss is experienced at all the indoor locations. This is due to the larger elevation grazing angle compared to the BS location closer to the building. The closer the BS is to the building, the more strong the impact of the diffraction will be.

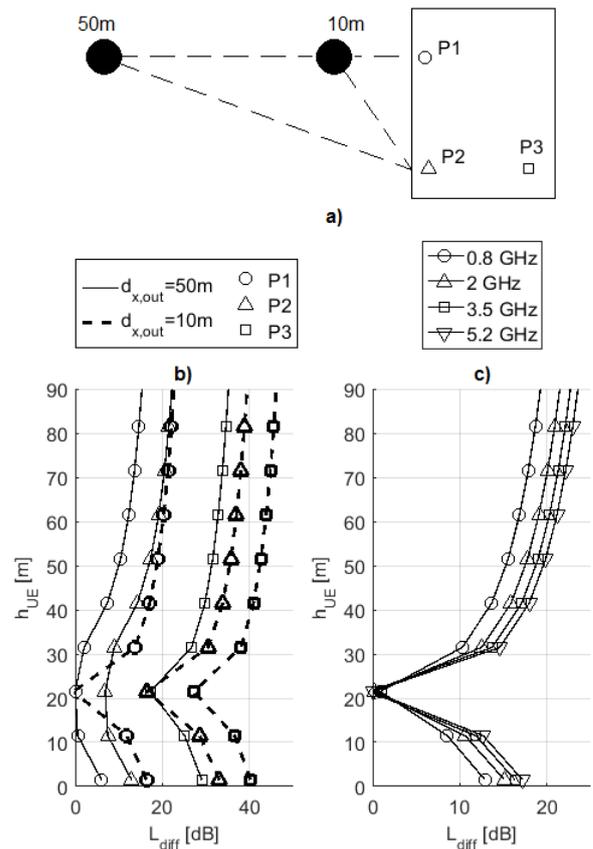


Fig. 2. Illustration of the model dynamics: a) top view of the example scenario considered, b) azimuth and elevation behavior for the selected indoor locations P1, P2 and P3, and c) frequency behavior for P1 and $d_{x,out} = 10$ m.

With respect to the frequency behavior of the model, as illustrated in Fig. 2.c for point P1, it is possible to observe how the diffraction component scales correctly with frequency, predicting slightly higher loss at higher frequencies.

As it has been shown, the model has physical sense and the trends predicted by the model match reality. It is worth to mention that a previous version of this model, considering only diffraction in the elevation domain and simple angular compensation in azimuth was used in different network evolution simulation studies for high-rise building scenarios, exhibiting already realistic and trustworthy results [5, 13].

III. MEASUREMENT-BASED MODEL VALIDATION

In order to validate the model against real data, two different and independently-obtained sets of measurements were considered. The first one, obtained in China, provides data for two buildings and a wide range of geometrical situations at a particular frequency of 3.5 GHz. This set of data is used in Subsection III.A for testing and validating the model in comparison with other models. The second one, obtained in Denmark, contains data for three buildings at specific geometrical situations, but for 4 different and simultaneously-recorded carrier frequencies: 0.8, 2, 3.5 and 5.2 GHz. This data set is used in Subsection III.B for performing the multi-frequency validation of the model.

TABLE I
SUMMARY OF THE DIFFERENT MEASUREMENT RANGES PER SCENARIO

Building	f [GHz]	h_{BS} [m]	h_{UE} [m]	$d_{x,out}$ [m]	d_y [m]	$d_{x,in}$ [m]
BUPT CMCC	3.5	5, 10, 25, 37 5,10	5.1-41.8 (floors 1-13) 13.2-87.3 (floors 3-22)	9, 19, 64, 95, 215 9,19	0.5-15.4 1.8-10.2	0.4-10.3 10.4-13.4
AAL1 AAL2 AAL3	0.8, 2, 3.5, 5.2	7	1.6-37.7 m (floors 0-12) 1.6-35.6 (floors 0-11) 1.6-48.7 (floors 0-16)	3 5 4	2 2 1	2 3 3

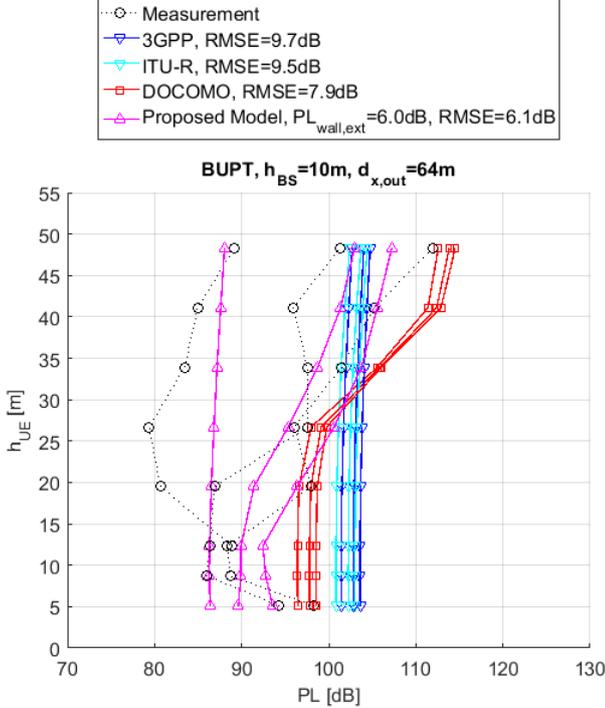


Fig. 3. Comparison between measurements and the predictions of the different models for 3 selected indoor locations.

Overall, the measurement data set size consists on over 2500 data samples. Further details and pictures of the measurement setups used in the different campaigns can be checked out in [11] and [14]. Table I summarizes the different measurement ranges for the selected scenarios. From it, the validity range of the model can be bounded. The model is valid for frequencies below 6 GHz, h_{BS} of 5-37 m, h_{UE} up to 90 m (equivalent to buildings of 30 floors with 3 m/floor), and $d_{x,out}$ up to 200 m.

A. Model Validation at 3.5 GHz

The model is tested and validated against the measurements performed in China at the BUPT and CMCC buildings at 3.5 GHz. In order to illustrate the limitations of the existing models, also the 3GPP [3], ITU-R [4] and DOCOMO [9] models are considered and their predictions are compared to the ones of the proposed model. In favor of making a fair comparison between the different models, the offset of the 3GPP, ITU-R and DOCOMO models have been tuned by adjusting the constant part of their penetration loss values, and thus minimizing their error. Once the offsets are adjusted, it is possible to have a fair comparison between the trends predicted by the different models.

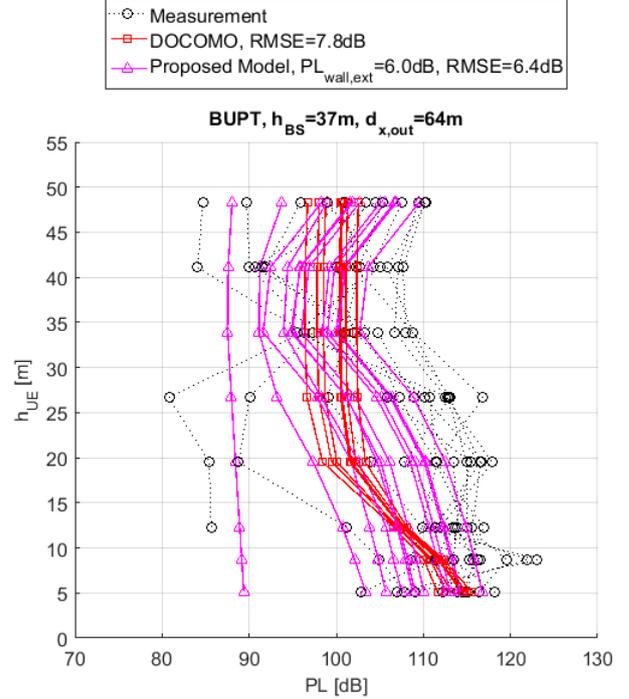


Fig. 4. Comparison between the predictions of the proposed model and the DOCOMO model for an entire cloud of indoor measurement locations.

Fig. 3 presents the prediction from the different models for three selected UE points across the different floors inside the BUPT building with the BS located at $h_{BS} = 10$ m and $d_{x,out} = 64$ m. The indoor points are located at the same $d_y = 12$ m (some horizontal grazing angle effect), one really close to the external wall at $d_{x,in} = 0.4$ m and the other two deeper indoor at $d_{x,in} = 2$ m and $d_{x,in} = 8$ m. As it can be seen, the proposed model matches well all the three different situations. The other models predict mainly the average vertical trends, but are not able to discriminate the UEs closer to the external facade of the building. It can be observed that both the 3GPP and ITU-R models lead to very similar predictions. The DOCOMO model is better than the 3GPP and ITU-R at predicting the correct vertical trends.

The entire cloud of indoor measurement points with $d_y = 0.5 - 15.4$ m and $d_{x,in} = 0.4 - 10.3$ m for the BUPT building is shown in Fig. 4 for $h_{BS} = 37$ m and $d_{x,out} = 64$ m. As it can be seen, the proposed model is able to predict the same dynamics observed in the measurements, while the DOCOMO model predicts a very similar trend for all the points independently of the indoor location.

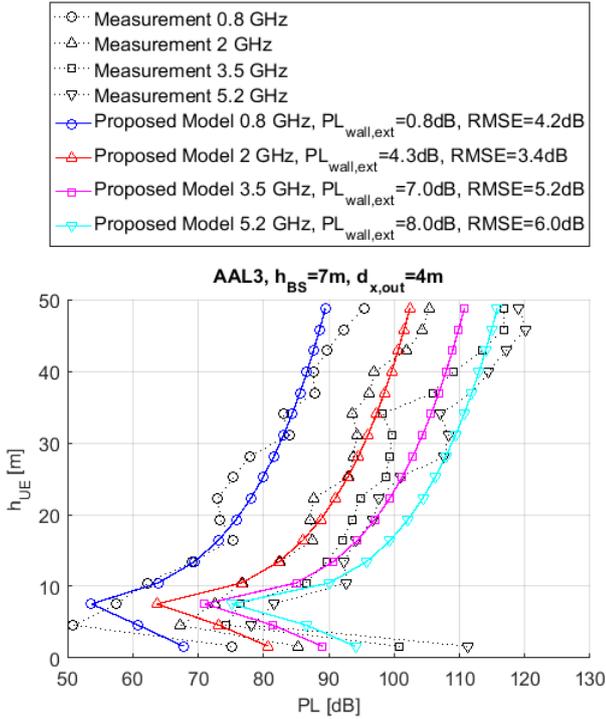


Fig. 5. Illustration of the matching of the model for the different frequencies for the AAL3 building.

The situations represented in the previous examples are repeated for the other explored geometrical combinations in both the BUPT and CMCC buildings. The matching of the different models is summarized in Tables II and III. By considering all the different situations and both buildings, the 3GPP and ITU-R models present a very similar root-mean-square error (RMSE) in the order of 9-10 dB. As the DOCOMO model predicts slightly better the vertical trends, the RMSE is reduced to 7-8 dB. The proposed model exhibits the best overall RMSE, with approximately 6-7 dB, about 1-3 dB better than the other models.

B. Multi-Frequency Validation

In order to evaluate the frequency behavior of the model, the multi-frequency measurements taken at the different AAL buildings in Denmark at 0.8, 2, 3.5 and 5.2 GHz are used.

Fig. 5 shows the matching between the model and the measurements at the AAL3 building for the different frequencies. A good matching is observed. As it can be noticed, the penetration loss values are distinct for the different frequencies. This is a normal fact, as the external wall attenuation is typically material and frequency-dependent. All the different attenuation values applied to the proposed model for the different building are aligned with the findings and values reported in [10].

Table IV summarizes the matching of the model to the measurements at the different frequencies for the 3 AAL buildings. As it can be seen, the RMSE is very low and quite constant across frequencies.

TABLE II
SUMMARY OF THE MATCHING OF THE DIFFERENT MODELS TO THE MEASUREMENTS FOR THE BUPT BUILDING

h_{BS} [m]	$d_{x,out}$ [m]	RMSE [dB]			
		3GPP	ITU-R	DOCOMO	Proposed
5	9	11.5	9.8	8.1	9.2
	19	11.1	10.8	7.7	7.9
	64	9.4	9.3	7.8	6.3
	95	9.9	9.7	9.0	6.7
10	9	11.9	10.7	9.0	10.2
	19	10.0	9.6	8.1	7.9
	64	9.7	9.5	7.9	6.1
25	95	10.6	10.3	8.6	6.3
	64	8.7	8.6	8.5	6.6
	95	9.9	9.7	8.7	7.1
37	215	11.9	11.5	8.9	7.9
	64	8.2	8.3	7.8	6.4
	95	8.8	8.7	8.4	7.3
	215	13.0	12.9	9.4	6.2
AVG		10.4	9.9	8.4	7.5

TABLE III
SUMMARY OF THE MATCHING OF THE DIFFERENT MODELS TO THE MEASUREMENTS FOR THE CMCC BUILDING

h_{BS} [m]	$d_{x,out}$ [m]	RMSE [dB]			
		3GPP	ITU-R	DOCOMO	Proposed
5	9	11.3	9.8	7.0	5.6
	19	8.7	8.3	6.2	5.7
10	9	11.2	9.7	7.2	6.1
	19	8.0	8.3	6.7	7.0
AVG		9.8	9.0	6.7	6.1

TABLE IV
SUMMARY OF THE MATCHING OF THE PROPOSED MODELS ACROSS THE DIFFERENT FREQUENCIES FOR THE AAL BUILDINGS

Building	RMSE Proposed Model [dB]			
	0.8 GHz	2 GHz	3.5 GHz	5.2 GHz
AAL1	4.0	5.0	5.0	4.5
AAL2	3.7	6.4	5.9	5.5
AAL3	4.2	3.4	5.2	6.0
AVG	4.0	4.9	5.4	5.3

IV. CONCLUSIONS

A novel geometrical height gain model for line-of-sight urban micro cells was presented in this paper. The model, founded on simple physical and geometrical relationships, is able to capture indoor situations that current existing models do not consider. Path loss compensation in both vertical and horizontal domains is introduced by means of simple knife-edge diffraction calculations. The model was validated against two independently-obtained sets of measurements performed at different locations in China and Denmark for a wide range of geometrical situations and frequencies below 6 GHz. The model was proved to have a RMSE accuracy in the order of 6-7 dB, 1-3 dB better than current existing models.

APPENDIX A

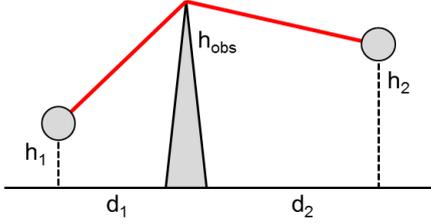
MATHEMATICAL FORMULATION AND NUMERICAL SOLUTION OF THE KNIFE-EDGE DIFFRACTION MODEL

By considering a single edge, the knife-edge diffraction loss (*KEDL*) can be computed from the Fresnel integral equation as follows:

$$h = h_{obs} - \frac{d_1 \cdot (h_2 - h_1)}{d_1 + d_2} - h_1 \quad [\text{m}]$$

$$\nu = h \cdot \sqrt{\frac{2 \cdot (d_1 + d_2)}{\lambda \cdot d_1 d_2}} \quad [-]$$

$$KEDL(f, h_1, h_2, h_{obs}, d_1, d_2) = 20 \cdot \log_{10}|F(\nu)| \quad [\text{dB}]$$



The numerical solution to the diffraction loss expression above can be obtained from the Lee approximation [12]:

$$|F(\nu)| = \begin{cases} 1 & \nu \leq -1 \\ 0.5 - 0.62\nu & -1 < \nu \leq 0 \\ 0.5 \cdot \exp(-0.95\nu) & 0 < \nu \leq 1 \\ \frac{0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2}}{\nu} & 1 < \nu \leq 2.4 \\ \frac{0.225}{\nu} & \nu > 2.4 \end{cases}$$

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