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Unified Propagation Model for Wi-Fi, UMTS and WiMAX Planning in Mixed Scenarios

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Abstract—**This paper presents an unified and empirical propagation model to obtain the received power in mixed scenarios, with outdoor and indoor environments, or in a scenario with only one kind of environment, either for an urban, sub-urban or rural scenario, with or without vegetation. This unified model is called the Lisbon University Institute (LUI) one and can be included into planning tools for wireless communication systems. The developed model is suitable for Path Loss prediction in mobile, as well as fixed wireless network systems, e.g., Wireless Fidelity, Universal Mobile Telecommunications System and Worldwide Interoperability for Microwave Access, considering Line-of-Sight or Non-Line-of-Sight propagation conditions.**

Keyword—LUI Model, Unified Model, Propagation Model, Outdoor, Indoor, Mixed, Path Loss, Wi-Fi, UMTS, WiMAX.

I. INTRODUCTION

Wireless communications cover an important role in the evolution of the communication and information society. In order for a user to take full advantage of recent wireless communication systems, it is necessary that an engineering team uses planning and optimization techniques that contribute to its quality improvement. Hence, it is normal to use planning tools that, aided by propagation models and Geographical Information Systems (GIS), have the capacity of simulating and even perform the planning of a wireless system in virtual reality. For the sake of accuracy it is required that both the propagation models and GIS are able to represent the reality in the best way possible.

Along with new technologies, some of them operating in quite large areas at higher frequencies, to guarantee an appropriate service quality, it is necessary to evaluate how voice and multimedia applications behave for indoor and outdoor environments, simultaneously. Therefore, it is essential that the range of validity for the propagation models includes such high frequencies while being able to estimate the signal power in a single or mixed scenario.

Since propagation models are usually adjusted to a specific range of frequencies and for a given type of operating channel or physical environment, the purpose of this work is to develop a generalized and unified propagation model (the Lisbon University Institute, LUI, Model) able to predict the path loss (PL), considering several telecommunications systems, e.g., Wireless Fidelity (Wi-Fi), Universal Mobile Telecommunications System (UMTS) and Worldwide Interoperability for Microwave Access (WiMAX). The model here proposed is innovative and may be included into wireless communication system planning tools. The main contribution from this work is the accurate estimation of the received signal power in a scenario that is simultaneously represented by one or two types of environment (e.g., outdoor and indoor) and for a range of frequencies that allow the planning with the above mentioned technologies.

The remaining of the paper is organized as follows. In Section II several well known propagation models are described as well as their potentialities and limitations. Section III proposes the LUI model and gives a brief explanation on its development. Section IV describes (in detail) the parameters to be used in the LUI model for each type of environment. Finally, Section V presents the main conclusions.

II. PROPAGATION MODELS

Propagation models are primarily aimed to predict the power of the received signal as it propagates from the transmitter to the receiver. These models provide an average value and its variation at that point, which can be useful to define goals and objectives for wireless communication systems design.

Due to the large variety of scenarios, there are several propagation models, each of them optimized for a particular environment. Wireless networks can operate into two main environments:

- Outdoor, where the signal propagates in open space, usually with cell radii of the order of kilometres (macrocells) or hundreds of metres (microcells),
- Indoor, where propagation takes place in a closed space and is usually associated with a cell radius of the order of tens of metres (picocells).

Normally, a propagation model is only applicable to one of these environments. In the context of wireless planning tools, the most used propagation models (and respective environments) are the following:

- Scenarios with only outdoor environments: Young [1], Okumura [1], Okumura-Hata [1], COST 231 Hata [2], Electronic Communication Committee-33 (ECC-33) [3], COST 231 Walfisch-Ikegami [4], Erceg [5], Erceg Modified [6] and Stanford University Interim (SUI) [7] models;
- Scenarios with only indoor environments: International Telecommunication Union-1238 (ITU-1238) [8], Multi-Wall [9], and Seidel-Rappaport [10].

In general, all propagation models have limitations on their use, but the principal limitation is the frequency range. Fig. 1 shows the frequency range for several known and most common outdoor and indoor propagation models.

In addition to the frequency range, there are other limitations/aspects that may significantly influence the prediction signal, such as the height of the base station (BS) or the terminal antenna height, particularly for outdoor propagation models.

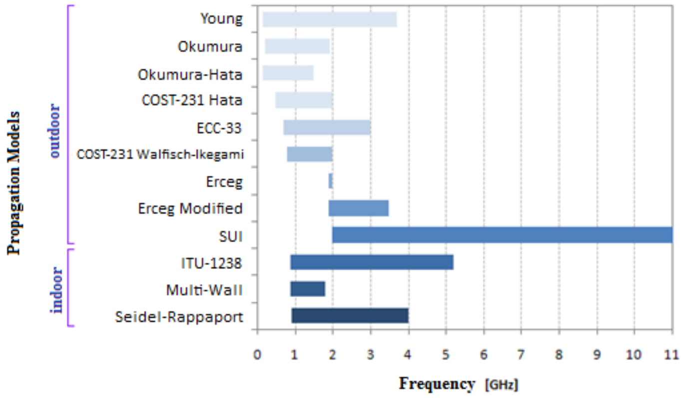

Figure 1. Frequency range covered in each model.

Some outdoor models were developed by changing the base station and terminal heights in the associated experimental trials. This led to propagation models that own correction factors that facilitate to correct the resulting PL prediction, depending on the nature of the scenario. Figs. 2 and 3 illustrate the range of base station and terminal heights, respectively (allowed in several outdoor propagation models).

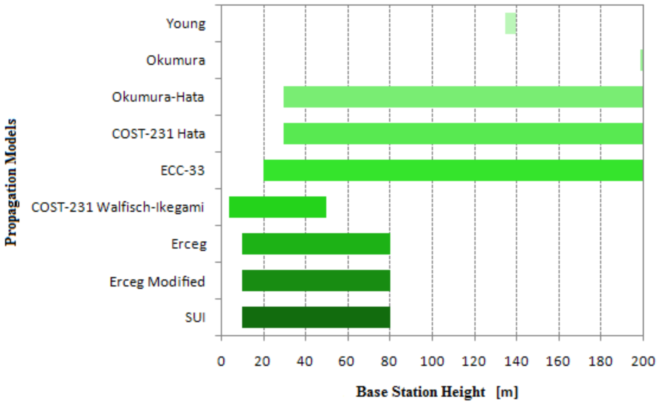

Figure 2. Range for the BS height in outdoor models.

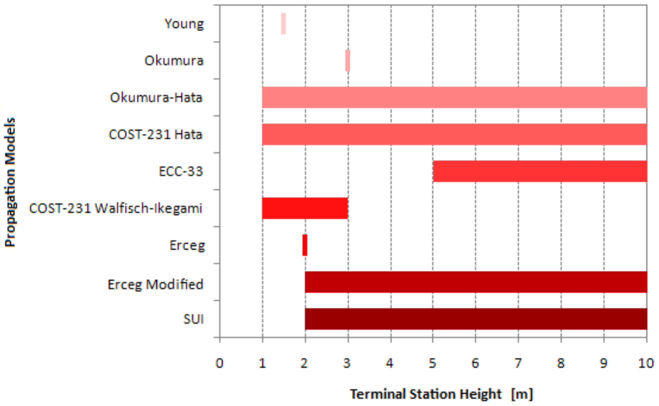

Figure 3. Range for terminal station height in outdoor models.

III. LISBON UNIVERSITY INSTITUTE MODEL

A. Main Objective

The Lisbon University Institute (LUI) model is a unified and empirical model, whose main objective is to predict the received power in any kind of scenario: indoor, outdoor or mixed (outdoor and indoor). It has also the capability to accommodate the additional attenuation caused by vegetative zones and involves three types of technologies (Wi-Fi, UMTS and WiMAX) operating within picocells, microcells and macrocells, respectively.

B. Description

The proposed model is based on four main components:

- Signal prediction in outdoor environment;
- Signal prediction in indoor environment;
- Signal prediction losses due to vegetation;

- Signal prediction losses due to penetration or transition environments.

The options taken during its development are the following:

- *Outdoor environment:* In order to account for Wi-Fi, UMTS and WiMAX, the model has to consider, at least, frequencies in the range 2.2–3.8 GHz. A comparison between the models, illustrated in Fig.1, enable us to conclude that the most suitable models for this range of frequencies are the Young, Erceg Modified and SUI ones. Although the Young outdoor model presents an adequate correlation with experimental results at 150, 450 and 900 MHz, the high correlation is not verified for higher frequencies [1]. Besides, this model was only validated in the city of New York, where the urban topology, with skyscrapers, is totally different from European city topologies. The Young model was validated for a BS height of about 140 m, which is not generally viable in Europe. Differently from the Young model, both Erceg Modified [6] and SUI [7] models include correction factors for the antenna height that are valid for Line-of-Sight (LoS) and Non- LoS (NLoS) propagation conditions. The SUI model is an extension of the Erceg one and it is valid for the 2–11 GHz frequency range, which includes the 2.2–3.8 GHz range of our proposal. Besides, as it was proposed together with the IEEE 802.16 group, it is one of the models recommended by the IEEE 802.16 group for WiMAX radio planning [11]. This justifies the choice of the SUI model for the outdoor component.
- *Indoor environment:* The most likely choices for the unified model indoor component are the ITU-1238 [8] and Seidel Rappaport [10] ones. Although ITU-1238 is a statistical model and does not need a detailed description of the propagation environment, it is not very reliable. On the other hand, Seidel-Rappaport is a direct ray empirical model and according to Hawbaker and Rappaport [12], Motley and Keenan [13] and Devasirvatham et al. [14], this model showed a high correlation with experimental results for the 900–4000 MHz frequency band, which includes the frequency range assumed for the LUI model. As a consequence, together with the Cheung-Saw-Murch model [15], which distinguishes the signal behaviour before and after the first obstacle, it was adopted as the indoor component of the unified model we propose.
- *Vegetation:* To account for the additional PL caused by vegetation, we considered the ITU-833 model [16], which is supported by detailed studies and it is validated by experimental results.
- *Indoor Penetration:* Due to the variety of possible materials at the outdoor-to-indoor interface, it is extremely difficult to predict the indoor received power while considering that transmitters are placed outdoors. Besides, the height of receivers relatively to the transmitter is also relevant. It is expectable that the PL is higher for the lowest floors while, for the highest floors, it is not so high, as the probability of existence of LoS propagation is higher. The range of values for floor height gain is extracted based on our experimental results. Besides, several publications show that the angle between the transmitter-receiver direction and the outdoor-to-indoor interface also has an impact on the received power. Although the limited number of published experiences makes the comparison difficult, the COST-231 model, further explored by Borjeson and De Backer [17], includes the PL owing to the type of material and this interface angular dependence.

C. Proposed Model

The average PL between transmitter and receiver as a function of the distance, is given by (1), where *NE* is the total number of environments, *ENV* represents the environment, *VEG* the type of vegetation, u[.] and u(.) are unit step functions (discrete and continuous, respectively), d_0 is the reference distance, λ is the wavelength, d_{bp} is the breakpoint distance, γ_1 and γ_2 are the PL exponents at different distances (before and after the breakpoint), X_f and X_h are frequency correction factors, A_m, d_{depth} and β are parameters for the additional vegetation loss, W_e, W_{GE}, θ, θ_H and θ_V are parameters related to the buildings penetration loss, G_f is the floor height gain, *NF* is the number of floors, *NW* is the number of walls, *FAF* is the floor attenuation factor, *WAF* is the wall attenuation factor while floor and wall are variables that identify each floor and wall through the path, respectively. A detailed description for these parameters follows:

- $NE \in \{1,2\}$ represents the number of propagation environments for the path between transmitter and receiver. In a mixed scenario, *NE*=2, and only for an indoor or outdoor scenario, *NE*=1.
- *ENV*=0 for indoor and *ENV*=1 for outdoor. This parameter represents the environment.
- *VEG* stands for the type of vegetation. *VEG*=1 if the point (at a distance, *d*, from the transmitter) considered for the computation of the received power inside a region with vegetation; *VEG*=0 otherwise.
- The meaning for the breakpoint distance, d_{bp}, is twofold:
  i) If only the indoor environment is included in a scenario, the propagation loss has two distinct regions, as a function of distance [15]. In the first region, within the 5–20 metre range from the transmitter, the propagation loss is similar to the free space one; hence at distances very close to the antenna, obstructions such as walls and floors do not interact significantly with the propagating waves. For higher distances, there is a significant increase in the propagation loss, as the electromagnetic waves become obstructed by the ceilings or walls of the rooms in the building. The distance at which this transition in propagation loss occurs is referred to as the breakpoint distance;
  ii) If the transmitter antenna is mounted in an outdoor environment, the breakpoint distance represents the distance between transmitter antenna and the interface for the indoor environment.

$$PL(d)_{[dB]} = \left\{ \begin{array}{l} 20 \cdot \log_{10}\left(\frac{4\pi \cdot d_0}{\lambda}\right) + 10 \cdot \gamma_1 \cdot \log_{10}\left(\frac{d}{d_0}\right) \cdot \mathrm{u}\left(d_{bp} - d\right) + \\ + ENV \cdot \left[X_f + X_h + VEG \cdot A_m \cdot \left[1 - \exp\left(\frac{-d_{depth} \cdot \beta}{A_m} \right) \right] \right] + \\ + \mathrm{u}[NE - 2] \cdot \left[W_e + W_{GE} \cdot (1 - \sin\theta)^2 - G_f \right] \cdot \mathrm{u}\left(d - d_{bp}\right) + \\ + (1 - ENV) \cdot \left[\begin{array}{l} \mathrm{u}[1 - NE] \cdot \left(\begin{array}{l} 10 \cdot \gamma_1 \cdot \log_{10}\left(\frac{d_{bp}}{d_0}\right) + \frac{WAF_{bp}}{\sin\theta_H} + \\ + \frac{FAF_{bp}}{\sin\theta_V} + \sum\limits_{floor=2}^{NF} \frac{FAF(floor)}{\log_{10}(10 \cdot floor)} \end{array} \right) + \\ + 10 \cdot \gamma_2 \cdot \log_{10}\left(\frac{d}{d_{bp}}\right) + \sum\limits_{wall=2}^{NW} \frac{WAF(wall)}{\log_{10}(10 \cdot wall)} \end{array} \right] \cdot \mathrm{u}\left(d - d_{bp}\right) \end{array} \right\} \quad (1)$$

- According to Cheung et al. [15] and Seidel and Rappaport [10], a value was proposed for the reference distance d_0=1 metre for picocells, while Erceg et al. [5] and Abhayawardhana et al. [2] suggested d_0=100 metres for macrocells. For microcells, we were not able to find a proposed value, so we proposed a new one based on our experimental results.
- The following meaning stands for the propagation exponents γ_1 and γ_2: i) when the prediction is performed for an outdoor-to-indoor environment, γ_1 represents the value for the outdoor environment while γ_2 refers to the indoor one; ii) when the prediction is performed for only an indoor environment, γ_1 represents the PL exponent before the first obstacle, i.e., up to the breakpoint distance, while γ_2 represents the PL exponent after the breakpoint; iii) when the prediction is performed for a single outdoor environment, only γ_1 is considered.

  In the case of UMTS and WiMAX technologies, where the base station is implemented in an outdoor environment, γ_1 is given by the following equation (the same which is used in the SUI model [7]):

  $$\gamma_1 = a - b_{[m^{-1}]} \times h_{b[m]} + \frac{c_{[m]}}{h_{b[m]}} \quad (2)$$

  where the parameters a, b e c, are constants that characterize the type of scenario involved, urban, suburban or rural, and their values are defined by the experimental results. For indoor Wi-Fi planning, the Access Point (AP) is usually mounted on the top of the floor, ranging from 3 to 4 metres from the ground. In the case of outdoor planning, the height of the AP may vary, depending on the scenario. However, there are no references to compare results in this range. Therefore, the parameter γ_1 is also obtained from experimental results for Wi-Fi planning.
- X_f and X_h are correction factors for the frequency, f, and the effective height, h_t, at the receiver terminal, respectively:

  $$X_{f[dB]} = 6 \cdot \log\left(\frac{f_{[MHz]}}{2000}\right) \quad (3)$$

  $$X_{h[dB]} = -\kappa_{TEC} \cdot \log\left(\frac{h_{t[m]}}{2}\right) \quad (4)$$
- As these parameters were inspired on the SUI model, which is only valid for macro-cellular systems, it was necessary to change it to incorporate three different communication technologies operating at three totally different types of cells. As a consequence, κ_{TEC} was introduced, a constant that represents the dependence of X_h on the cell dimensions (and on the considered technology).
- The building penetration loss parameters have the following meaning: W_e is the interface loss, in dB, when the wall is perpendicularly “illuminated” by the transmitter (θ=90º) towards the receiver, as shown in Figure 4; W_{GE} refers to the additional interface loss, in dB, if the interface is “illuminated” from an angle θ (0º < θ < 90º) with the horizontal axis. For a prediction scenario with two environments (NE=2), the angle θ is between the transmitter and the interface. In an indoor scenario, θ represents the angle between the transmitter and the breakpoint (or first wall or obstacle) either in a horizontal plane, θ_H, or in a vertical one, θ_V.

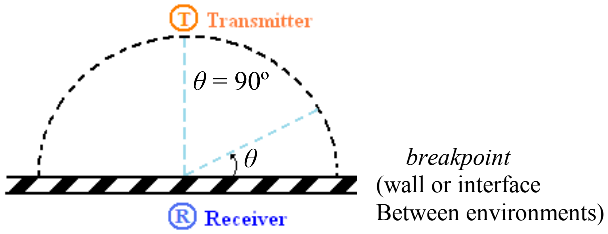

Figure 4. Application of the angle θ in the penetration loss model.

- The floor height gain, G_f, depends on the height of the terminal in the building, on the existence of LoS between the transmitter and the receiver, on the interface type and on the operating frequency, among other factors. Therefore, its value was also obtained from experimental results.
- *NF* and *NW* represent the number of floors and walls, respectively, crossed by the direct ray between the transmitter and the receiver. *NF* is only used if the transmission antenna is mounted in an indoor environment. If the antenna is mounted outdoors and the receiver is indoors, it is assumed that the dominant path towards the receiver, the one corresponding to the highest propagation energy, is guided by the interface that corresponds to the respective floor.
- The Floor Attenuation Factor (*FAF*) represents the attenuation (loss) caused by the up or down surfaces of each floor, while they are between the transmitter and receiver. Also, the Wall Attenuation Factor (*WAF*) refers to the walls between the transmitter and receiver. These parameters are normally expressed in dB. However, it is important to note that *FAF* is not considered in a mixed scenario. *FAF* and *WAF* are used in expressions representing how the signal crosses floors and walls, which account for all obstacles between the transmitter and the receiver. The impact of multipath increases when the direct ray is obstructed by further obstacles. As a consequence, the PL from new obstacles is lower. This model incorporates therefore the effect of multipath, as ray tracing techniques do, e.g., Uniform Theory Diffraction (UTD) applied in optical ray models (which account for reflection and diffraction by means of the information on the exposed material taken from the tool database). These expressions only refer to the path after the breakpoint.

IV. PARAMETERS FOR LUI MODEL

According to [18], several experimental trials were taken for validating the LUI model. All experimental trials assumed at least one scenario, with a mixed scenario for each technology, except for Wi-Fi, which was also tested in a scenario including only an indoor environment.

The LUI model showed us that it behaves differently for each scenario. During the adjustments made through experimental results, Tables 1, 2 and 3 served as a summary of parameters used in the model for the three technologies considered.

In Table 2, h_t and h_b, represents the effective terminal antenna and BS heights, respectively. Three types of terrain are distinguished in Table 3: A, B and C. Type A presents a terrain with the highest path loss, and may be used for hilly terrain areas with moderate or very dense vegetation. Terrain type B is mainly a characteristic of flat terrains with moderate or very dense vegetation or hilly terrains with rare vegetation. Type C is suitable for flat terrains with rare vegetation where path loss is the lowest.

Parameters	**Wi-Fi**	**UMTS**	**WiMAX**
f [Hz]	2.4×10^9	2.2×10^9	3.5×10^9
d_0 [m]	1	25	100
κ_{TEC}	24	10.8	20

Table 1. Parameters to be used in the LUI model for the three technologies.

γ_1 parameters	**Terrain Category**		
	A	***B***	***C***
a	5.15	4.0	3.6
b [m^{-1}]	0.0075	0.0065	0.0050
c [m]	14.6	17.1	20.0

Table 2. Parameters for γ_1, to be used in the LUI model for outdoor or mixed UMTS and WiMAX scenarios, considering different terrain categories.

V. CONCLUSIONS

This paper describes a new empirical and unified propagation model to predict the PL for three wireless technologies. The proposed model was adjusted with experimental results. However, to be incorporated in a planning tool, this model had to be improved with an extensive and exhaustive campaign of measurements.

The LUI model covers the range of frequencies from 2.2 to 3.5 GHz, where the three technologies (Wi-Fi, UMTS and WiMAX) operate, as well as other technologies, for example, the promising Long Term Evolution (LTE). This model can also be generalized for a higher range of frequencies, due to its correction factors.

Parameters	**Indoor**	**Mixed**		
	Wi-Fi	***Wi-Fi***	***UMTS***	***WiMAX***
γ_1	3	3.85	Table 2	Table 2
γ_2	2.5	3.35	$\gamma_{1\,\mathrm{UMTS}} - 0.5$	$\gamma_{1\,\mathrm{WIMAX}} - 0.5$
G_f	–	$\begin{cases} 1.285 \cdot h_t - 3.285 &, h_t \leq h_b \\ -0.857 \cdot h_t + 13.85, & h_t > h_b \end{cases}$	$\begin{cases} 2.097 \cdot h_t - 17.41 &, h_t \leq h_b \\ -1.758 \cdot h_t + 44.93, & h_t > h_b \end{cases}$	Not tested
X_h	–	Add topographic height difference to the effective height of the terminal	Do not add topographic height difference to the effective height of the terminal	Do not add topographic height difference to the effective height of the terminal

Table 3. Parameters to be used in the LUI model for the three technologies by type of scenario.

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