# Experimental Characterisation and Modelling of the Reflection of Infrared Signals on Indoor Surfaces

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#### Abstract

The performance of non-line-of-sight indoor wireless infrared communication systems depends on the reflection characteristics of the surfaces that surround the communication space. This paper presents a set of measured reflection patterns of the most common indoor surfaces and the approximation of those experimental patterns using two reflection models: the model of Lambert and the model of Phong. The results show that the reflection pattern of many surfaces present a strong specular component. Those patterns are well approximated by the model of Phong, but not by the model of Lambert. It is also shown that the use of the model of Lambert to approximate the reflection pattern of specular surfaces can lead to errors of several dBs in the evaluation of the propagation losses.

## 1 Introduction

The development of indoor wireless communication networks using infrared (IR) radiation was first proposed by Gfeller in 1978 [6, 5]. Since then, the use of IR technology to establish short distance wireless communications has verified a considerable increase, that is well visible on the growing number of publications on related subjects [9, 2, 17, 8, 13, 11, 12, 10]. Indoor wireless IR systems are based in one of the following emitter-to-receiver configurations: (i) line-of-sight, (ii) quasi-diffuse or (iii) diffuse. The operation of line-of-sight systems relies on a free path between emitter and receiver, which have to be pointed to each other. In quasidiffuse systems, emitter and receiver have to be directed to the same surface, that reflects part

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of the optical beam towards the detector. In diffuse systems, emitter and receiver have wide radiation and collecting patterns and the optical signal may go into the receiver after multiple reflections on the surfaces that surround the communication cell. This configuration does not impose any particular requirement on the emitter and receiver orientation, which represents an important advantage from the users point-of-view. The operation of quasi-diffuse and diffuse systems relies on the existence of surfaces with good reflection characteristics within the communication cell. Therefore, to design high performance non-line-of-sight IR systems, an accurate knowledge of the reflection characteristics of the most common indoor surfaces is required.

The reflection characteristics of any surface depend on several factors, namely, the surface material, the wavelength of the incident radiation and the angle of incidence. The roughness of the surface relative to the wavelength is also determinant on the shape of the reflection pattern. A smooth surface reflects the incident radiation in a single direction (like a mirror), while a rough surface reflects the incident radiation in several directions. The Rayleigh criterion is commonly used to decide if a surface is smooth or rough [4]. According to this criterion, a surface can be considered smooth if

$$\zeta < \frac{\lambda}{8\sin\theta_i} \tag{1}$$

where  $\zeta$  is the maximum height of the surface irregularities,  $\lambda$  represents the wavelength of the incident radiation and  $\theta_i$  is the angle of incidence. For IR radiation with  $\lambda = 800 \ nm$  and assuming normal incidence, a surface is rough for values of  $\zeta > 0.1 \ \mu m$ . This result shows that most of the indoor surfaces are rough for IR radiation and, therefore, their reflection patterns present a diffuse component.

In his pioneer work, Gfeller [5] considered that the IR reflection pattern of most of the indoor surfaces could be correctly approximated using the model of Lambert. He also found that most of the indoor surfaces would have an IR reflection coefficient between 0.4 and 0.9. Since then, these results have been extensively used on the design of indoor IR systems. The simulation of the indoor optical channel can benefit significantly the design of high performance IR systems, but requires models that approximate correctly the channel characteristics. In this paper, we present a set of experimental results showing that the model of Lambert is not able to approximate correctly the reflection pattern of several indoor surfaces, but the model of Phong allows to approximate all those patterns quite well. Section 2 reviews two models frequently used to approximate the reflection of optical signals:

the model of Lambert and the model of Phong. In Section 3, we present a set of measured reflection patterns for surfaces that are common in indoor environments. The approximation of the measured patterns using the models of Lambert and Phong is also studied. To evaluate the error introduced by the reflection model used in the simulations, Section 4 presents the single reflection propagation model that considers only one reflection of the emitted signal to approximate the propagation of IR signals in indoor spaces. In Section 5, we evaluate the error introduced on the results of the propagation losses by considering the model of Lambert, instead of the model of Phong, to approximate the reflection pattern of a varnished wood surface. Section 6 presents the main conclusions.

## 2 IR Reflection Models

Infrared radiation shows propagation characteristics very similar to the visible light. In this section, we describe two reflection models commonly used to approximate the reflection of visible light on computer generated images: the model of Lambert and the model of Phong.

#### 2.1 The Model of Lambert

Some surfaces are completely irregular and reflect IR signals without privileging any particular direction. Those surfaces look equally bright when observed from different directions. The reflection patterns of those surfaces are completely diffuse and can be correctly approximated using the *model of Lambert* [14], which is described by

$$R(\theta_o) = \rho R_i \frac{1}{\pi} \cos(\theta_o) \tag{2}$$

where  $\rho$  is the surface reflection coefficient,  $R_i$  represents the incident optical power and  $\theta_o$  is the observation angle. The expression shows that the shape of the reflection pattern does not depend on the incidence angle. This fact makes the model simple and easy to implement in software. Figure 1 illustrates a lambertian reflection model. The line in bold represents the direction of incidence and the gentle line corresponds to the direction of specular reflection.

#### 2.2 The Model of Phong

The reflection pattern of several rough surfaces is well approximated by the model of Lambert, except around the specular reflection direction, where the pattern presents an intense component. Moreover, the model of Lambert is not able to approximate the mirror like reflection patterns of smooth surfaces. Phong [16] developed a model that allows to approximate



Figure 1: A lambertian reflection pattern.

correctly those reflection patterns. The model considers the reflection pattern as a sum of two components: one diffuse and other specular. The percentage of each component depends mainly on the surface characteristics and is a parameter of the model. The diffuse component is modelled using the expression of the model of Lambert (Eq. 2). The specular component is modelled by a function that depends on the incidence angle  $(\theta_i)$  and on the observation angle  $(\theta_o)$ . The model of Phong is described by

$$R(\theta_i, \theta_o) = \rho \frac{R_i}{\pi} \left\{ r_d \cos(\theta_o) + (1 - r_d) \cos^m(\theta_o - \theta_i) \right\}$$
(3)

where  $\rho$  represents the surface reflection coefficient,  $R_i$  is the incident optical power and  $r_d$ is the percentage of incident signal that is reflected diffusely and assumes values between 0 and 1. The parameter m controls the directivity of the specular component of the reflection. It should be noted that the model of Lambert is obtained from the model of Phong when  $r_d = 0$ . Figure 2 illustrates a typical reflection pattern simulated using the model of Phong, that is described by  $R(45^\circ, \theta_o) = \frac{0.5}{\pi} [\cos(\theta_o) + \cos^{45.3}(\theta_o - 45^\circ)]$  ( $\theta_i = 45^\circ$ ). The line in bold



Figure 2: Typical reflection pattern described by the model of Phong.

represents the direction of incidence. The pattern has the main lobule centred around the direction of specular reflection  $\theta_r = 45^{\circ}$  (gentle line). The model of Phong depends on both  $\theta_o$  and  $\theta_i$  and, therefore, it is more complex than the model of Lambert. The computation time required to simulate the propagation of IR signals on indoor environments can be significantly higher when using the model of Phong.

## 3 Modelling of Experimental Reflection Patterns

A comparative study of the reflection models presented above has to consider two aspects: (i) the ability to approximate correctly the reflection pattern of most surfaces commonly found in indoor spaces and (ii) the efficiency in terms of computation resources. The first aspect can only be evaluated by modelling experimental patterns. For that purpose, we measured a large set of reflection patterns and tried to approximate them using the reflection models described in previous section. We started by the model of Lambert and, when the results were not satisfactory, we proceeded with the model of Phong.

An experimental characterisation of the reflection pattern of a surface requires a large set of measurements. To speed-up this process, we developed a semi-automatic set-up that uses a computer controlled step-by-step motor. Figure 3 illustrates the set-up. A sample



Figure 3: Semi-automatic set-up to measure reflection patterns.

of the material to be characterised is fixed to the motor axle. To measure each reflection pattern, the IR emitter is fixed relatively to the surface sample and is pointed to a specific point on that sample. That point has to be coincident with the motor rotation axle and will be designated by *reflection point*. The IR detector is also directed to the same point on the sample. The set-up allows scanning the observation angle (angle between the surface normal and the detector normal) and measure the corresponding values of the surface reflection pattern in an automatic way. Each experimental pattern results from a set of measurements for different observation angles carried out on a semi-circle with centre on the reflection point.

The IR emitter is an LED with a half-power angle (hpa) of 4°, that emits at 820 nm. The receiver uses an PIN detector with field-of-view (fov) of approximately 1.5°. To minimise the environmental noise, all the measurements were done on a dark room. Moreover, to minimise the noise introduced by the set-up system and radio frequency interference, each measurement was repeated several times and the average of the measured values was considered. The reflection pattern of several surfaces that are common in indoor spaces were measured, namely, cement (before and after painting), wood (before and after varnishing), ceramic floor tile, formica, white paper, brown pasteboard and glass. The following sections present the measured reflection patterns in polar diagrams.

#### 3.1 Surface of Cement

Cement surfaces are one of the most frequent in indoor spaces. The reflection pattern of a rough surface of cement was measured for a set of different incidence angles, before and after painting the surface with white plastic dye. Figure 4 shows the experimental reflection patterns for  $\theta_i = 45^\circ$ , measured before and after the surface has been painted. The figure



Figure 4: Experimental reflection patterns of a surface of cement, and their approximation through the model of Lambert.

shows also the approximation of the measured patterns using the model of Lambert. The surface reflection is quite diffuse and the model of Lambert is able to approximate correctly the measured patterns. The curves of the model of Lambert were adjusted to the experimental values using the *NonLinear Fitting* routines of Mathematica [18]. The curve that approximates the measured pattern of the unpainted surface is  $R(\theta_o) = 300 \cos(\theta_o)$ , while

the curve that approximates the pattern measured after painting the surface is described by  $R(\theta_o) = 710 \cos(\theta_o)$ . The results show that painting the surface in white originated an increase in the reflection coefficient, but the shape of the pattern remains almost unchanged. The patterns are almost lambertian due to the roughness of the surface. The reflection characteristics were also measured for other angles of incidence. We have verified that the measured patterns were almost lambertian and that the reflection coefficient decreases with the incidence angle.

#### 3.2 Surface of Wood

The reflection pattern of a surface of wood was measured for different angles of incidence, before and after varnishing the surface. Figure 5 shows the measured reflection patterns for  $\theta_i = 0^\circ$  and  $\theta_i = 45^\circ$ , and the approximation of those patterns using the model of Lambert. The curves show that the reflection patterns are almost diffuse and the model of Lambert is



Figure 5: Experimental reflection patterns of a surface of wood and their approximation using the model of Lambert.

able to approximate them correctly. For  $\theta_i = 0^\circ$ , the experimental values are approximated by  $R(\theta_o) = 911 \cos(\theta_o)$ .

The surface of wood was varnished and the measurements were repeated. Figure 6 presents the measured patterns and their approximation using the models of Lambert and Phong. The results show that varnishing the surface originated a significative change on the reflection pattern characteristics. The measured reflection patterns shows a strong specular component and the model of Lambert was not able to approximate them correctly. The model of Phong was then considered and allowed to approximate correctly the measured patterns, as shown



Figure 6: Experimental reflection patterns of a surface of wood varnished and their approximation using the models of Lambert and Phong.

in the figure. Both curves of the model of Phong are described by

$$R(\theta_i, \theta_o) = 2987[0.3\cos(\theta_o) + 0.7\cos^{97}(\theta_o - \theta_i)]$$
(4)

where  $\theta_i$  takes, for each curve, the value of the angle of incidence:  $0^{\circ}$  or  $45^{\circ}$ . This expression was obtained through curve-fitting using Eq. 3 with  $\theta_i = 0^{\circ}$ .

It is interesting to compare the curves of Phong, that approximate the measured patterns, with a curve of the model of Lambert corresponding to the same total reflected power. Figure 6 shows also that lambertian reflection pattern, for  $\theta_i = 0^\circ$ . The condition of equal total reflected power for both curves is described by

$$\oint_{2\pi} k \cos(\theta_o) d\Omega = \oint_{2\pi} k' \left[ r_d \cos(\theta_o) + (1 - r_d) \cos^m(\theta_o) \right] d\Omega$$
(5)

where k and k' represent the amplitude of the patterns of Lambert and Phong, respectively, and  $2\pi$  corresponds to the solid angle of the surface reflection hemisphere. To a plane angle  $\theta_o$  corresponds a solid angle of  $\Omega = 2\pi (1 - \cos(\theta_o))$ , therefore  $d\Omega = 2\pi \sin(\theta_o) d\theta_o$ . Solving both integrals, and after a few simplifications, we obtain

$$k = k' \left[ r_d + 2 \frac{1 - r_d}{m+1} \right] \tag{6}$$

Substituting the parameters k',  $r_d$  and m of Eq. 4 results in k = 973. Therefore, the curve corresponding to the model of Lambert in Figure 6, is described by

$$R(\theta_o) = 973\cos(\theta_o) \tag{7}$$

The results of the figure show that the model of Phong is able to approximate correctly the experimental patterns, however, the same is not true for the model of Lambert. We also conclude that varnishing the surface results on a small increase of the reflection coefficient.

#### 3.3 Surface of Formica

Figure 7 shows the reflection patterns of a surface of formica measured for incidence angles of  $0^{\circ}$  and  $45^{\circ}$ , and their approximation using the models of Lambert and Phong. The curves of



Figure 7: Experimental reflection patterns of a surface of formica and their approximation through the models of Lambert and Phong.

the figure show that the surface reflection patterns are dominated by the specular component of the reflection. This fact results from the smoothness and mirror-like characteristics of the surface of formica. The experimental patterns are well described by

$$R(\theta_i, \theta_o) = 4541[0.14\cos(\theta_o) + 0.86\cos^{112}(\theta_o - \theta_i)]$$
(8)

where  $\theta_i$  assumes, for each curve, the corresponding value of the incidence angle. The figure presents also a curve of the model of Lambert, that corresponds to the same total reflected power as the curve of the model of Phong for  $\theta_i = 0^\circ$ . The curve of Lambert is described by  $R(\theta_o) = 705 \cos(\theta_o)$  and was obtained through a process similar to that used for the surface of varnished wood. The model of Phong approximates well the measured patterns, however, the same is not true for the model of Lambert.

#### 3.4 Surface of Glass

Surfaces of glass are also frequent in indoor spaces. Figure 8 shows the measured reflection patterns of a surface of glass for incidence angles of  $0^{\circ}$  and  $45^{\circ}$ , and their approximation



Figure 8: Experimental reflection patterns of a surface of glass and their approximation using the model of Phong.

using the model of Phong. The curves show that the experimental patterns are completely dominated by the specular component of the reflection. The expression of the model of Phong that approximates the surface reflection pattern was fitted to the values measured for  $\theta_i = 0^\circ$ and is given by

$$R(\theta_i, \theta_o) = 4397[0.0\cos(\theta_o) + 1.0\cos^{280}(\theta_o - \theta_i)]$$
(9)

where  $\theta_i$  assumes, for each curve, the value corresponding to the incidence angle. The results show that the experimental patterns are correctly approximated by the model of Phong.

The reflection patterns of other surfaces, commonly found in indoor spaces, were also measured and modelled. The model of Lambert was able to approximate correctly the reflection pattern of several rough surfaces [15]. The reflection pattern of a surface of white paper was well approximated by  $R(\theta_o) = 780 \cos(\theta_o)$ . The reflection pattern of a brown pastecard was modelled by  $R(\theta_o) = 670 \cos(\theta_o)$  and the pattern of a ceramic floor tile surface by  $R(\theta_o) = 200 \cos(\theta_o)$ .

#### 3.5 Discussion of Measured and Modelling Results

The results presented in previous sections show that the model of Lambert is not able to approximate appropriately the reflection patterns of several surfaces, commonly found in indoor spaces, namely, varnished wood, formica and glass. The model was able to approximate well the reflection of IR signals in rough surfaces of cement and unvarnished wood. The reflection patterns of surfaces of cement painted in white, white paper and brown pastcard have similar characteristics. Surfaces of unpainted cement and ceramic floor tile have a smaller reflection

coefficient.

It was also verified that the model of Phong was able to approximate correctly the reflection patterns of all the surfaces considered in this study, which are a representative sample of the surfaces commonly found in indoor spaces.

### 4 Single Reflection Propagation Model

In indoor spaces it is frequent that only the ceiling surface has good reflection characteristics or the room surrounding walls are too far way. The operation of IR communication systems in those spaces has to be based on line-of-sight or quasi-diffuse configurations. Line-of-sight configurations are very susceptible to interruption of the direct path between emitter and receiver and require frequent re-alignments of the transceivers. Quasi-diffuse configurations are based on a single reflection of the emitted signal and are able to reduce considerably those limitations. In this section, we present a model for the propagation of optical signals in quasi-diffuse systems, considering only one reflection of the emitted signal. This model will be designated by *single reflection propagation model* and will serve to estimate the error in the propagation losses introduced by the use of the model of Lambert to approximate the reflection pattern of some surfaces.

The single reflection propagation model assumes that only one surface reflects the IR radiation. The model allows to evaluate the impulse response of quasi-diffuse channels. The reflecting surface is divided in a large set of very small areas, named reflector elements. These elements are, first, considered as collecting areas and the temporal and spatial distributions of the emitted signal on those reflectors are evaluated. Then, each small reflector is considered a point source that emits the collected signal multiplied by the surface reflection coefficient. The reflection pattern of each element follows one of the reflection models presented in Section 2. The collected signal is the sum of all the signals that go into the detector, after being reflected on the different elements. Due to differences in the signal paths, the collected signal presents temporal dispersion. However, we are only interested in evaluating the effect of the used reflection model on the channel propagation losses and will not consider the signal propagation delays. The accuracy of the model increases with the reduction of the area of the reflector elements. Figure 9 illustrates the geometry considered to describe the single reflection propagation model. Consider a large reflection surface S divided into small elements with area  $\Delta A = \Delta s \times \Delta s$ , where  $\Delta s$  is the spatial resolution. Consider also an



Figure 9: Geometry used to describe the single reflection propagation model.

emitting source and a detector, both directed to the reflection surface. The source emits a total power  $P_t$  with an half-power angle of hpa. The detector presents an active area  $A_D$  and a field-of-view fov. The power incident on the differential element j is given by

$$P_j(t) = P_t \frac{m+1}{2\pi} \cos^m(\phi_{Ej}) \cos(\theta_j) \frac{\Delta A}{d_{Ej}^2}$$
(10)

where  $\phi_{Ej}$  and  $\theta_j$  are the angles of emission and incidence of the optical signal and  $d_{Ej}$  is the distance from the emitter to the reflector j. The accuracy of this equation depends on the validity of the condition  $d_{Ej} \gg \Delta s$ . The optical signal collected at the detector after being reflected by the element j is given by

$$P_{jR}(t) = P_j(t)R(\theta_j, \phi_j, S) \frac{D(\theta, fov)}{d_{jR}^2}$$
(11)

where the function  $R(\theta_j, \phi_j, S)$  represents the reflection pattern of the element j. This pattern depends on the reflection characteristics of the surface S and follows one of the models described by Eqs. 2 or 3. The total collected power after one reflection on S can be approximated by the sum of the  $P_{jR}(t)$  corresponding to all the elements j that are in the field-of-view of the detector and is given by

$$P_{R}(t) = \sum_{j=1}^{M} P_{t} \frac{(m+1)A_{D}\Delta A}{2\pi d_{Ej}^{2} d_{jR}^{2}} \cos^{m}(\phi_{Ej}) \cos(\theta_{j}) R(\theta_{j}, \phi_{j}, S) \cos(\theta_{jR})$$
(12)

where M is the total number of differential elements j that are in the field-of-view of the detector. We should note, that this equation is only valid on the condition  $d_{jR} \gg \sqrt{A_D}$  and the accuracy of the result obtained increases with the spatial resolution used. The value of  $\Delta s$  required depends on several factors: distance from the emitter to the reflection surface,

emitter radiation pattern, distance from the surface to the detector, fov of the detector and reflection characteristics of the surface.

## 5 Influence of the Reflection Model on the Channel Propagation Losses

In Section 3, we verified that the reflection pattern of several surfaces, commonly found in indoor spaces, are not correctly approximated by the model of Lambert. In this section, we evaluate the error that the use of the model of Lambert may introduce on the evaluation of the propagation losses. This study is based on the single reflection propagation model.

Consider a quasi-diffuse system, operating in a space where the only surface that reflects the IR signals is the ceiling, which is a varnished wood surface. Consider also that the surface reflection pattern was the one measured in Section 3. The emitting source has  $P_t = 1 W$  and  $hpa = 1^{\circ}$  and the detector has  $A_D = 1 \ cm^2$  and  $fov = 85^{\circ}$ . Emitter and receiver are on the same plane,  $1 \ m$  above the floor and move along a straight line, the xx axis. The simulations considered the reflection models of Eq. 4 (model of Phong) and Eq. 7 (model of Lambert), presented in Figure 6.

The propagation losses are evaluated for two configurations of the transceivers: (a) emitter and detector are vertically oriented (*natural orientation*) and (b) emitter and receiver are ideally oriented to the same point in the centre of the reflecting surface (*perfect orientation*). Figure 10 illustrates those system configurations.



Figure 10: Quasi-diffuse system configurations: a) Natural orientation. b) Perfect orientation.

Consider the system configuration with natural orientation of the transceivers. Because of the homogeneity of the reflection surface and as emitter and receiver are pointed vertically, the propagation losses present azimuth symmetry around the source axis. Figure 11 presents the channel propagation losses versus the receiver position for three different emitter positions. The results show that the model used to approximate the reflection pattern of the surface



Figure 11: Propagation losses for a quasi-diffuse system with natural orientation, considering the reflection models of Lambert and Phong.

of varnished wood affects the results obtained for the propagation losses, mainly around the source position. Using the model of Lambert, the minimum value of the propagation losses is  $30 \ dB/cm^2$ , while using the model of Phong that values changes to approximately  $25 \ dB/cm^2$ . The model of Phong originates also a value of the maximum propagation losses slightly higher than the model of Lambert.

Consider now a system configuration with emitter and receiver perfectly pointed to the same point on the reflecting surface, corresponding to the cell centre. Figure 12 shows the propagation losses for different positions of the emitter over the axis xx: 0, -3, -6 and -9. The results were evaluated considering both models of reflection. The figure shows the propagation losses along the axis xx (that passes through the position of emitter and receiver), because the maximum difference in the results obtained for both models happens on that direction. The results are presented for several positions of the emitter, but the curves obtained using the model of Lambert are almost coincident. When the emitter is on the centre of the cell, position (0, 0, -3), the maximum difference on the results is almost 5 dB, obtained when the receiver is at the same position. As the emitter moves towards the cell border, the maximum difference in the results increases slightly, and the receiver position (-x, 0, -3), the maximum difference happens when the receiver is near the position (x, 0, -3). This fact results from the specular component of the reflection pattern (model of Phong).



Figure 12: Propagation losses of a quasi-diffuse system with perfect orientation of the transceivers and considering the models of Lambert and Phong.

When emitter is at the cell border, position (-10, 0, -3), the maximum difference between both curves is 9.6 dB, obtained when the receiver is at (10, 0, -3). These results show that the model used to approximate the surface reflection pattern may introduce a significant error in the evaluation of the propagation losses, mainly when the emitter is distant from the cell centre.

The influence of the reflection model on the results obtained for the propagation losses depends not only on the surface reflection pattern but also on the source beam-width and position. Figure 13 illustrates the influence of the source hpa on the propagation losses, considering a quasi-diffuse system with perfect orientation of the transceivers. The emitter is fixed at position (-8, 0, -3) and the receiver moves along the horizontal line defined by  $-10 \le x \le 10$ , y = 0 and z = -3. The curves are shown for values of hpa of 1°, 5°, 10°, 20° and 60°. The results show that the maximum difference between the curves corresponding to the models of Lambert and Phong decreases rapidly with the value of hpa. The maximum error introduced by using the model of Lambert, instead of the model of Phong, is almost 8 dB at position (7, 0, -3), for  $hpa = 1^{\circ}$ , it is smaller than 2 dB, for  $hpa = 10^{\circ}$  and there is only a slight difference between the curves corresponding to each model for  $hpa = 60^{\circ}$ . We should note that the error introduced by using the model of Lambert to approximate the surface reflection pattern would be greater for surfaces of formica or glass, as their reflection patterns have stronger specular components.

In the single reflection propagation model, described previously, the reflection surface is divided in a large set of small reflection elements. The accuracy of the obtained results



Figure 13: Influence of the source hpa on the propagation losses, considering the models of Lambert and Phong.

depends on the spatial resolution ( $\Delta s$ ) used on each simulation. To evaluate the effect of the spatial resolution on the obtained results, the simulations were done considering different values of  $\Delta s$ , between 1 and 50 cm. For values of  $\Delta s > 10.0$  cm, the collected power depends considerably on the spatial resolution used. This fact indicates that  $\Delta s$  should not be larger than about 10 cm. The computing time increases rapidly with the spatial resolution: for  $\Delta s = 50$  cm the computing time required was smaller than 1 s for both models, while for  $\Delta s = 1$  cm it was 152 s for the model of Lambert and 187 s for the model of Phong. The difference in the computing time for both models is not much significant because most of the simulation program is common to both models. However, if multiple reflections of the emitted signal were considered, the difference in the computing time would be more significant.

## 6 Conclusions

This paper described the measurement and modelling of the reflection patterns of IR signals on surfaces that are commonly found in indoor environments and its consequences in terms of propagation losses after one reflection. We considered two models to approximate the reflection of optical signals in indoor surfaces: the model of Lambert and the model of Phong. The results show that the reflection pattern of several surfaces present a strong specular component. The model of Lambert is simple but was not able to approximate correctly those reflection patterns. The model of Phong is more complex but was able to approximate correctly all the measured reflection patterns. The single reflection propagation model was described and used to evaluate the influence of the reflection model considered on the evaluation of the propagation losses. The results show that the use of the model of Lambert to approximate the experimental reflection pattern of a surface of varnished wood, instead of the model of Phong, may introduce errors of several dB on the results of the propagation losses.

The simulation of the propagation of optical signals in indoor spaces was previously investigated considering exclusively the model of Lambert to approximate the reflection pattern of all indoor surfaces [5, 9, 7, 3, 1]. The results of this work show that, when the source has a reduced hpa, the approximation of some reflection patterns using the model of Lambert may introduce significant errors on the results of the propagation losses.

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