Optical Wireless Communication: LOS/WLOS/DIF propagation model and QOFI software

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***Abstract*—Personal optical wireless communication is a promising solution for increasing the available communication bandwidth within a room. This technology can offer, with line of sight and diffuse propagation, very high-speed communication between portable devices. This paper presents a generic line of sight, wide line of sight (LOS/WLOS) propagation model and a diffuse (DIF) propagation model for the design of wireless optical communication. It also presents a software tool, with these models, offering the possibility to simulate the optic path loss models in a room. This simulation can be shown with furniture and Optical Wireless equipment in 2D or 3D view.**

***Index Terms*— OWN, Optical Wireless Network, Optical Wireless, Free Space Optic, FSO, Optical Wireless Communication, WON, Wireless Optical Network.**

I. INTRODUCTION

A detailed analysis of the link margin is an important factor for any communication system. For example, for optical fibre systems, the engineer examines the power level which is injected into the fibre at the transmitter side and then determines all the potential losses until the signal arrives at the receiver side. The receiver typically has a minimal sensitivity *Se* which is specific to a given data rate. This sensitivity represents the lower limit of the received optical power to maintain a predefined transmission quality. In order to guarantee link reliability, it is necessary to ensure that after having withdrawn all the losses, the received optical power remains above the threshold *Se*. However, an important difference lies in the nature of the losses between the transmitter and the receiver. Thus, in an indoor configuration, the personal optical wireless system (POW) clearly suffers from channel fluctuations according to the link margin, the equipment orientations, obstacles and the distance between devices. To make the connection more reliable, it is judicious to preserve an optical link margin larger than the threshold *Se*. However, assigning a large link margin could possibly decrease the potential distance between the transmitter and the receiver. This step presents the compromise between distance and reliability. So, in a given environment, a precise analysis must be made. In what follows, we describe LOS/WLOS and DIF models describing the link margin and considering the devices as a black box having very few but homogeneous technical characteristics. Thus, we present a software tool which has integrated these models and other parameters, in order to simulate the optic budget link in any kind of room.

II. PROPAGATION TYPES AND DEFINITIONS

There are several typologies of propagation in limited space for POW links. Figure 1 shows that the propagation between the transmitting source and the receiving cell can be divided into three main categories [1], [5]:

- line of sight (LOS) propagation,
- wide line of sight (WLOS) propagation,
- diffuse (DIF) propagation.

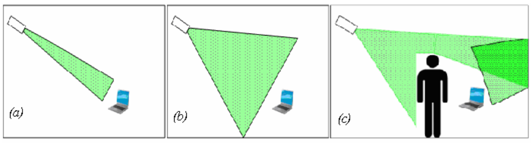

Fig. 1: propagation typologies

The LOS propagation is the simplest typology in optical wireless systems and the most used in connections between point-to-point communication systems in indoor and outdoor environments. In this configuration, the transmitter and the receiver must be oriented towards one other to establish a permanent or temporary link by removing any obstacle between them. The WLOS typologies are characterized by transmitters with more important divergence angles (DIV) and receivers having a larger field of view (FOV). In a DIF configuration, independent of the obstructing objects, the link is always maintained between the transmitter and the receiver. This is thanks to multiple reflections of the optical beam on surrounding surfaces such as ceilings, walls, and furniture. In this case, the transmitter and the receiver are not necessarily directed towards one other; the transmitter benefits from an important beam divergence and the receiver has a very large FOV.

In the following section, we propose a helpful set of definitions for the main parameters that should be considered when studying the performance of a POW system.

We define P_t as the average optical power transmitted through the optical radiation source. In optics, the transmitted signal itself is a power, so the quantity P_t can be simply seen as the average of the optical transmitted signal. In general, it is expressed in mW, W, or in dBm. It can also be expressed as a power per unit area or per solid angle. In general, the divergence of the transmitted beam is characterised by a solid angle measured in steradians, radians or degree. We then define the half power angle (*HP)* by the angle between the direction of the normal axis to the source corresponding to the maximum transmitted optical power and the direction corresponding to half of this power. *HP* is expressed in mrd, rd, or in degrees and the value is specified at -3 dB. In the same way, the receiver *FOV* is given by the angle between the normal axis to the receiver corresponding to the maximum received optical power and the direction corresponding to a half of this power. It is expressed in mrd, rd, or in degrees. Like *HP*, the value is specified at -3 dB. The effective area of the receiver A_{eff} is the equivalent surface of the optical receiver taking into account the real surface of the photodiode, the optical concentration module, and the optical filter. A_{eff} depends on the reception angle, and is expressed in m^2 or in mm^2. As described in the introduction, the receiver sensitivity *Se* represents the lower level limit of the received optical power to ensure quality, transmission reliability, and data rate. At the receiver side, the received optical power must remain above *Se,* after taking into account all the losses. It is expressed in mW, W, or in dBm.

III. LOS/WLOS LINK MARGIN ANALYSIS

The transmitter device can be characterised by P_t and *HP*. Considering a generalised Lambertian model [2] for the source, it is possible to determine its parameter *m* from the angle *HP*:

$$\cos(HP)^m = 1/2 \Rightarrow m = \log(1/2)/\log(\cos(HP)) \quad (1)$$

It becomes possible to calculate the transmitted optical power according to a semi-angle of transmission *φ*:

$$P(\varphi) = \frac{m+1}{2\pi} P_t\left(\cos(\varphi)^m\right), \text{ with } \varphi \in [-\pi/2, \pi/2] \quad (2)$$

On the other hand, the receiver device is characterised by three other major parameters:

- its sensitivity *Se*,
- its effective area A_{eff} ,
- its Field Of View *FOV*.

A_{eff} will be given according to the normal direction, and from *FOV*, it is possible to calculate the effective area according to a semi-angle of reception *ψ* different from the normal and its parameter n by:

$$A_{eff}(\psi) = A_{eff}\cos(\psi)^n, \quad 0 \le \psi \le \pi/2 \quad (3)$$

We can suppose that the distance *d* between the transmitter and the receiver is relatively large compared to the size of the photo detector. The equation of the channel frequency response at null frequency, or DC channel gain will be:

$$H(0) = A_{eff}(\psi)\frac{P(\varphi)}{P_t}.\frac{1}{d^2} \quad (4)$$

Where φ and ψ are the transmission and reception semi-angles defined with respect to the normal axes to the transmitter and the receiver respectively. Obviously, this equation only holds if ψ does not exceed *FOV*. The value of geometrical attenuation in dB can be given by:

$$Att_{geo} = 10 \log H(0) \qquad (5)$$

The average optical received power P_r will be :

$$P_r = H(0) P_t \qquad (6)$$

We define the link margin M_l of an optical link as the optical received power available above the receiver sensitivity *Se*:

$$M_l = P_r - S_e \qquad (7)$$

Where: M_l: the link margin (dB),
P_r: the received optical power (dBm),
S_e: the receiver sensitivity (dBm),

IV. DIF LINK MARGIN ANALYSIS

This section covers the diffuse (DIF) propagation model. The main spatial discretization method described by John BARRY and J.M. KAHN [4] deals with a meshing of walls in a finished number of elementary surfaces. The impulsional response is recursive. Having determined the channel impulsional response, we can then calculate the frequency response and estimate the channel bandwidth. Let us consider a rectangular, empty room where walls have a uniform reflection coefficient [3]. We consider a point infrared source. This non-directive source is described by a position vector r_s, a vector n_s giving the direction of the emission, its power P_S and the spatial characteristic of the radiation, given by $\Re(\phi,\theta)$. At first, we consider an emission with θ independent, described by the Lambert law, where n represents the mode number:

$$\Re_S(\phi) = \frac{n+1}{2\pi} Ps \cdot \cos^n(\phi)$$
$$\phi \in [-\pi/2, \pi/2] \qquad (8)$$

The source is completely described by the triplet: *S{r_s, n_s, n}*. The receiver has a position (r_R), an orientation (n_R), a surface (A_R) and a maximal FOV (field of view): $\Re$ {r_R, n_R, A_R, FOV}. Walls are divided into elementary reflectors (patches) considered as a receiver of area dA that receives a power dP. Then it becomes a secondary diffuse source that emits a power dP$\cdot\rho$, ρ being the coefficient of reflectivity for the pixel. The optical energy resulting from the source can arrive directly on the receiver, either directly or by reflection on walls. In these conditions, the impulsional response is described as follows:

$$h^0(t;S,\Re) \approx \frac{n+1}{2\pi} \cos^n(\phi) d\Omega \cdot rect(\phi/FOV) \cdot \delta(t - R/c) \qquad (9)$$

R: distance between the receiver and the source
θ: angle between n_R and (r_S –r_R)

$$\cos(\theta) = n_R \cdot (r_S - r_R)/R \qquad (10)$$

ϕ: angle between n_S and (r_S –r_R)

$$\cos(\phi) = n_S \cdot (r_S - r_R)/R \qquad (11)$$

The light can undergo an infinite number of reflections. Each term h(k) represents the response when the light undergoes k reflections.

$$h(t;S,\Re) = \sum_{\kappa=0}^{\infty} h^k(t;S,\Re) \qquad (12)$$

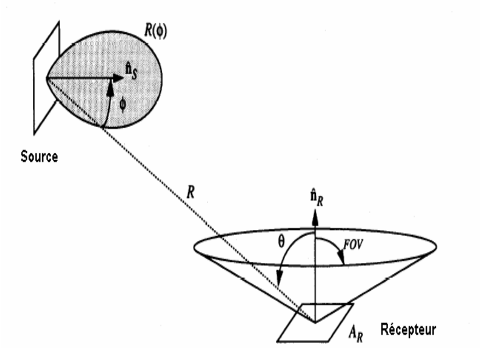

Fig. 2 : Emission/Reception configuration

$$h^{(k)}(t;S,\Re) \approx \frac{n+1}{2\pi} \sum_{i=1}^{N} \frac{\rho_r \cos^n(\phi) \cos(\theta)}{R^2} \cdot rect(\phi/FOV) \cdot$$
$$\cdot h^{(k-1)}(t - R/c; \{r,n,1\}, \Re) \Delta A$$

(13)

N: total number of elementary reflectors

Note that the spatial discretization leads to a temporal discretization.

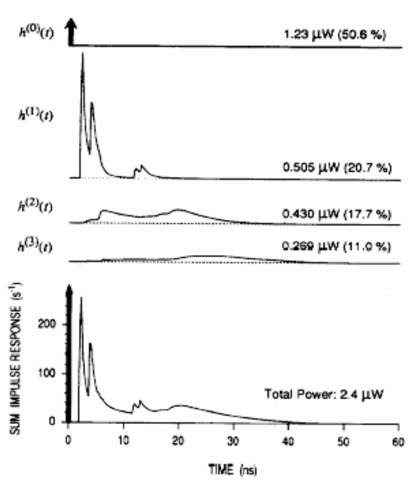

Fig. 3 : Example of impulse response

V. QOFI - IMPLEMENTATION PROCESS

Slightly different from other optic propagation models, the Nettle model [7] originates from the process of iterative calculation of a diffuse surface [8] or the illumination radiosity mechanism.
The radiosity is an illumination technique used in some three-dimensional (3D) representation models. This enlightenment is known as global illumination because each elementary surface cannot be calculated separately from the other. The all illumination transfert models can only be solved globally. The radiosity uses physical radiative formula light transfer between elementary diffuse surfaces composing a scene in 3D.
For instance, we can consider a simple scene modelled by using a polygonal mesh, an empty cubic room divided into small surface elements (patch). Each face of the cube and the room is a patch (figure 4).

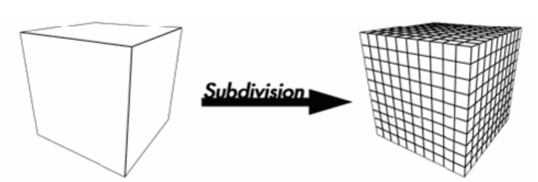

Fig. 4: 3D cube patch subdivision

Each patch will receive energy from another patch, absorb a part (depending on patch material properties) and return the other part to the others patches.
The energy transmitted from patch A to patch B is based on the following elements:

- Normal surface for the patches,
- A vector that represents the direction from the emission centre patch to the reception centre patch,
- The average distance between the two patches,
- The area of each patch,
- The amount of energy to be transmitted,
- The amount of visibility between the patches.

Some elements of the plan are defined as surfaces as a source optical emission. For each issuer, the surface elements plan that will be received is determined. The process is recursive radiosity and elements of illuminated surfaces at the given current sources are optical emissions for the next iteration.

More specifically, the emitted radiosity from patch i, (*Bi*) is equal to auto-emitted energy (*Ei*), plus all radiosity received from other patches j (*Bj*), weighted by patch reflectivity depending on the material (*Ri*).
The energy received by patch i from patch j is equal to the product of radiosity issued by patch j multiplied by a form factor ($F_{i\text{-}j}$), depending on i-j relative orientation, respective distance and the other furniture's presence (shadowing) between the two patches.

$$B_i = E_i + R_i \sum B_j F_{i-j} \qquad (14)$$

The form factor ($F_{i\text{-}j}$) is the emitted energy part from patch i and received by patch j. The equation can be simplified [9]:

$$F_{i-j} = \frac{\cos\theta_i \cos\theta j}{\pi r^2} H_{ij} dA_j \qquad (15)$$

With:
- Cosinus value of the angle from the normal,
- R: distance between the patches,
- H_{ij}: relative visibility between the surfaces of the two patches,
- DA_j: surface differential j.

This propagation calculating module allows the 3D scene calculation. It can not only deal with a patches scene, but can also calculate the propagation with a number "n" of iterations. This iterative calculation process is based on the global illumination techniques.
The process is as follows:
- After the 2D room creation which is associated with a 3D scene, this 3D scene can be generated by a 3D engine software (Ogre, for example) into its own data structures (tree nodes).

- While data is processing, room data is transferred to a Nettle module which takes the 3D tree and structure model. This is achieved by converting data into triangular 2D objects and identified by their 3D positions.
- When calculating, for each emission source and each iteration, patches that can be lit are determined according to the room geometry and the furniture inside it.

The result is effected by:
- The 2D propagation process results to the 3D engine software.
- A new 3D image file generation with room optical propagation results.

This optical wireless propagation calculation in 3D is made possible thanks to the propagation module allowing among others to divide the scene into patches and to calculate the route followed by a beam through the scene for 'n' iterations. This implementation is based on the Nettle radiosity technique module.

VI. QOFI - IFSO MODELING TOOL

This section deals with software - QOFI "Qualité de service Optique sans Fil Indoor"; a 3D modelling tool implemented in order to validate both LOS/WLOS and DIF models. This application lets the user create and model a 3D interior by building a room and inserting both 3D furniture and IFSO (Indoor free Space Optic) elements (gateways and end devices). In the edition mode, the user can add, move, rotate, delete objects in a 2D view and then visualise the scene in a 3D view. The application is based on the Ogre 3D engine and uses the Qt framework.

The interface is based on a main window including

- a 3D model library
- a 2D view
- a 3D view
- a property window

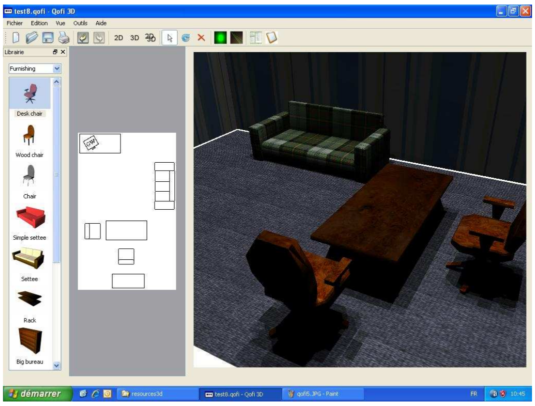

Fig. 5: QOFI MMI (Machine Man Interface)

Once the scene has been created, an IFSO simulation can be run using a LOS, DIF or LOS & DIF model (in download and upload transmissions); in order to view the reception areas in COVER mode.

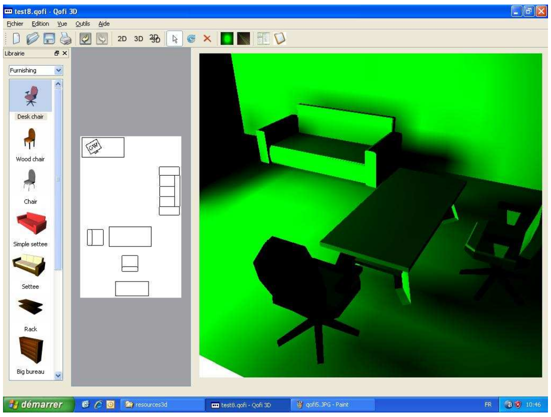

Fig. 6: Example of QOFI simulation

This application can also plot the impulsional response in LINK mode.

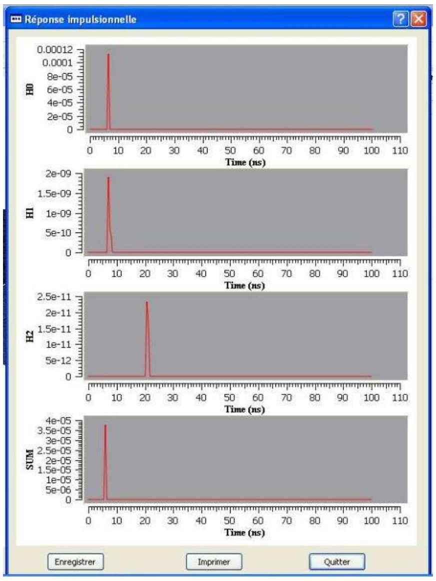

Fig. 7: Example of QOFI impulse responses

User cases relative to the simulation are the following ones:

- COVER downlink: emission from all the gateways
- COVER uplink: emission from a single end device
- LINK downlink: emission from all the gateways to an end device
- LINK uplink: emission from an end device to a gateway

VI. CONCLUSION

In this paper, we have presented a generic model of link margin analysis in LOS/WLOS and DIF configurations. We have shown that, for POW communication, this approach makes it possible to carry out a first level comparison between proposed indoor solutions. Thus, we have presented a software tool which has integrated these models and other parameters, in order to simulate the optic margin link for any room. However, improvements are also possible. For example, the radiated optical power is based on the generalised Lambertian model, but in the case of non circular symmetry around the normal axis of the transmission device, this assumption is no longer valid. It is then advisable to integrate new parameters to obtain a more adapted model. Another example is the 60 GHz material reflection parameters.

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