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Title: **Propagation Losses and Impulse Response of the Indoor Optical Channel: A Simulation Package**

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Abstract

In this paper we present a simulation package developed to calculate both the channel propagation losses and the multipath dispersion in the indoor optical channel. The simulation package is based on a model of the indoor optical channel which includes the total optical power and radiation pattern of the emitter, the channel free-space losses and reflection properties and the active area and fiel-of-view of the receiver. We illustrate the use of the simulation package by means of two case studies corresponding to: i) a satellite based cell and ii) a passive reflection based cell. It is seen that optimization of the emitting pattern by tunning the number, orientation and radiation pattern of the LEDs can significantly reduce the maximum channel losses.
This work is being carried out as part of the ESPRIT.6892 - POWER (Portable Workstation for Education in Europe) project commisioned by the CEC.

I - Introduction

The need and demand to communicate and share software applications, data bases and information in general while keeping mobility have increased very rapidly over the past few years. This growth required the development of practical and flexible communication networks. Wireless networks represent a very good alternative to cabled networks for indoor applications. Indoor wireless communication systems can be used in a wide range of applications to provide for portability, user mobility and easy setup networking.

Indoor wireless systems can use two kinds of carrier to convey the information: radio waves or infrared radiation. There are already systems commercially available using each of the technologies. The use of a particular technology depends mainly upon the envisaged application and the physical channel characteristics. In this work, we concentrate on indoor communication systems using infrared technology.

Recently, infrared technology based systems have been receiving significant interest because they:

- are easier to implement than radio systems.
- do not require any licensing.
- are not affected by electromagnetic noise interference and
- provide for privacy outside the room premises.

Indoor infrared systems are mainly impaired by three factors:

- Interference from ambient light (sun light and artificial illumination),
- Mutipath dispersion (for data rates higher than a few Mbit/s, depending on the room dimensions) and
- Technological limitations of the infrared devices available (LEDs and PIN photodetectors).

There are mainly three basic propagation modes on indoor infrared systems:

- *Point-to-point* communication links,
- *Quasi-diffuse* systems and
- *Diffuse* systems.

These modes have been extensively discussed in the literature [1] [2] [3]. The main interest of our study is the characterization of the indoor channel under the *quasi-diffuse* and *diffuse* propagation modes.

In this paper we present a simulation package developed to calculate both the channel propagation losses and the multipath dispersion. A brief discussion of the characteristics of the *quasi-diffuse* propagation mode is given in section II. The model of the optical channel used in the simulation package is presented and discussed in section III. In section IV we illustrate the use of the simulation package by means of two case studies. Finally, in section V we present the main conclusions and some guidelines for future work.

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II - The *Quasi-diffuse* propagation mode

In the quasi-diffuse mode the signal emitted by one station is broadcasted to all the other stations in the room. This requires emitters and receivers to have relatively large emitting beams and field-of-views, respectively. A direct line-of-sight between emitter and receiver is not required. However all stations must have a direct path to the reflecting surface. Usually, the reflecting surface is the room ceiling which must present good reflection characteristics. If the room ceiling surface does not reflect properly the infrared signals or if one intends to extend the coverage area an active reflector can be used. This active reflector also called "satellite" is mounted at the ceiling. The satellite receives the signal broadcasted by the emitting stations, amplifies the signals and then broadcasts them again. The satellite increases system complexity and cost and therefore its use should be avoided.

Two variations of the quasi-diffuse mode will be considered:

- Targeted orientation: assumes the user will have to point the optical interface of the transceiver to the satellite or to some specific area at the room ceiling if the system uses passive reflection.
- Natural orientation: assumes that all terminals have a large emitting beam and receiving *FOV* and all will be oriented vertically.

III - Model of the Indoor Optical Channel and Simulation Package

Before one invest in the design and implementation of a communication system it is fundamental to have an accurate model for the channel characteristics. In this section, we will present the model of the optical indoor channel used in the simulation package. The model includes the characteristics of the emitted optical beam, the effects of the channel over that beam and the receiver collecting characteristics. This model can be used for the evaluation of:

- the channel propagation losses and
- the channel impulse response.

The simulation package allows for optimization of the power distribution over the cell area. The optimization process has in view the reduction of the worst-case propagation losses.

The simulation package is being improved to obtain the impulse response of the indoor channel. For that purpose, multiple-order reflections from the room walls are being considered. The channel impulse response is important on the design of infrared indoor systems operating at data rates higher that a few Mbit/s.

The main characteristics of the quasi-diffuse indoor channel are now presented. The source emitted power is spread over the room space. The power spreading degree depends directly on the source position, orientation and radiation pattern. The emitted beam incides on the room walls and furniture and is partially reflected according to the reflection coefficients and patterns of the surfaces. The optical power collected at the receiver depends on the receiver position, orientation, fielf-of-view and active area. The received signal results from the direct signal (line-of-sight) and multiple-order reflected signals that incide into the detector active area. The signal collected from the multiple-order reflections will result on a signal spread or intersymbol interference.

The components of the optical channel are the optical sources, the room space and configuration and the optical collectors. Usually, the optical sources and collectors are formed by sets of LEDs and PINs, respectively. The models used in the simulation package will now be presented.

1) The source model

Indoor infrared communication systems usually use short wavelength (820-900 nm) Light Emitting Diodes (LEDs). Following Gfeller [1], the radiant intensity of a LED can be modeled using an extension of the Lambertian law given by:

$$E(\phi) = \frac{(n+1)}{2\times\pi} P_t \cos^n(\phi) \qquad (1)$$

where P_t (usually supplied by the manufacturer data sheets) is the total emitted power, ϕ is the angle with the perpendicular to the LED lens and n is a value given by

$$n = -\frac{0.693}{\ln[\cos(HPBW)]} \qquad (2)$$

where $HPBW$ is the LED half power emission angle. For HPBW=60° n is unity and Eqn. (1) reduces to the case of the ideal Lambertian radiator. The higher the value of n the more directive is the radiation pattern of the LED.

2) The Channel Propagation Model

There are mainly two independent factors influencing the channel propagation characteristics: the free-space propagation losses and the signal reflections on the room surfaces. The free-space losses under consideration are decribed by the $1/r^2$ law. Other characteristics of atmospheric systems, like signal attenuation, dispersion and scattering, are not considered since the ranges of indoor systems are very small and those effects are negligible.

The reflection characteristics of any surface depends upon the surface material and texture. The reflection pattern from a surface is usually composed of a diffuse and a specular component. There are several models describing the reflection properties of typical surfaces available from the literature [4]. The most appropriate model to use depends on the surface characteristics and also on the complexity of the model we are able to implement. We will consider the Lambertian reflection model which is characteristic of perfectly diffusing surfaces. It has been shown that this model is a good approximation for some surfaces [1]. Measurements of the reflection pattern of the most common room surfaces will be carried out and, if required, more complex models will be included in the simulation package.

In the simulation package, the reflecting surfaces are divided into incremental areas characterised by a reflection coefficient and a pure Lambertian radiation pattern given by

$$R(\beta)=\frac{1}{\pi}\cos(\beta) \tag{3}$$

where β is the emission angle. The incremental areas should be relatively small for the point source approximation to be satisfactory.

The simulation of the impulse response of the indoor optical channel requires high resolution and a very large number of incremental areas have to be considered. This factor will result in a simulation package requiring very demanding computational capabilities.

3) The Detector Model

In indoor wireless infrared systems, the most used detectors are large area silicon *Positive-Intrinsic-Negative*, *PIN*, photodetectors. To achieve larger collecting areas, without increasing the *PIN* capacitance, a lens to concentrate the incident radiation on the detector active area can also be employed. In both cases, the detector is modeled as having an active area which collects the power incident for angles smaller than the *FOV*. In the case of a lens being in use the transmitance factor of the lens has to be considered.

IV - Case Studies

In this section, the simulation package presented above will be used in the evaluation and minimisation of the channel propagation losses for two case studies corresponding to: a system with a satellite and a passive reflection based system. The optimization variable will be emitter radiation pattern, i.e., the number, orientation and radiation pattern of the LEDs forming the optical source.

A - System with Active Reflection

This case is representative of indoor infrared systems where the ceiling surface does not reflect the infrared radiation properly or an extension of the coverage area of the cell is required. The emitting satellite is on the ceiling center. The stations are distributed over a plane 1 meter above the room floor. The area of the cell is bounded by a circle with a given radius. The optical interfaces of the transceivers are considered to be always pointed vertically. The optimization is done for the downward link (satellite to transceiver). The main system physical parameters are presented in table 1.

Parameter	Value
Room Length	12 m
Room Width	12 m
Room Height	4 m
Cell Radius	6 m
Resolution	10 cm
Satellite Position	(0, 0, 0)
Source Array	13 LEDs
Total Emitted Power	152 mW
Receiver Plane	(x, y, -3)
Receiver Active Area	1.0 cm^2
Receiver Sensitivity	-46.1 dBm
Receiver *FOV*	85 degrees

Table 1 - Physical characteristics.of a system with active reflection

Through trial-and-error it has been found that an array of 13 commercially available LEDs emitting a total power of 152mW would be required to illuminate this cell, assuming a receiver sensitivity of -46.1 dBm typical of a full response Manchester receiver [5]. If other LEDs with more convenient radiation patterns were available the number of LEDs required would be decreased.
In the next sections, we calculate the propagation losses of a system with a satellite where all LEDs are oriented in the same direction both theoretically and through simulation. This has in view to illustrate the gains achieved with the optimisation process presented latter.

1) - Theoretical evaluation

The radiation emitted by the satellite is required to cover the whole cell area. Therefore LEDs with large *HPBW* are required. Commercially available LEDs with 55 degrees *HPBW* will be assumed. We also assume the LEDs to be all pointing down vertically and the photodetectors to be all pointed vertically to the ceiling. Due to the orientation of the emitting elements of the satellite, the maximum channel losses are at the boundary of the cell. Only the power that goes directly from the emitter to the receiver (line-of-sight) is considered.

The power collected, P_r, at a given position is given by:

$$P_r = \frac{(n+1)}{2\times\pi} P_t \cos^{(n+1)}(\phi) A_r \frac{1}{d^2} \qquad (4)$$

where P_t, n and ϕ are as defined in eqn. 1 (ϕ represents also the incidence angle on the detector), A_r is the active area of the optical detector and d is the distance between the emitting source and the detector. The maximum channel propagation losses were calculated by normalising eqn. 1 to the total emitted power and active area. The losses were 68.845 dB/cm^2 at position (6, 0, -3). The maximum and minimum irradiances are -32.18 dBm/cm^2 and -47.03 dBm/cm^2, respectively. Thus, the cell dynamic range is 14.85 dB.

2) - Simulation without optimization

Using the simulation package, the channel propagation losses were evaluated for the system configuration presented in last section. Figure 1 shows the resulting irradiance profile over the cell area assumed circular with a 6 meter radius.

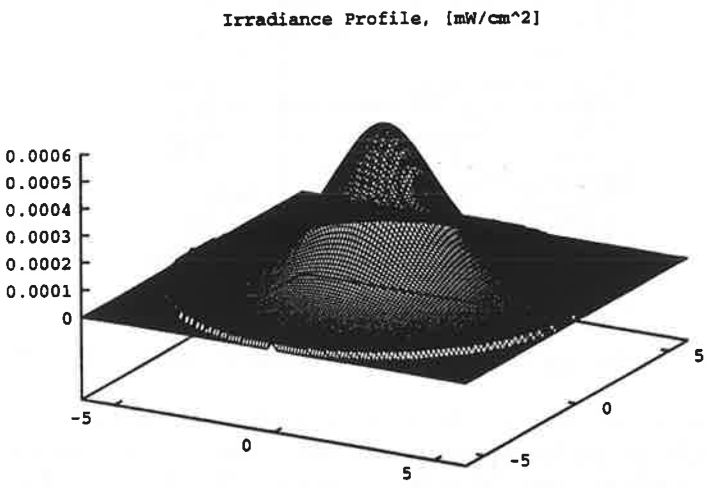

Figure 1 - Power density distribution profile without optimization.

According to the results, the maximum channel propagation losses are 68.849 dB/cm^2 at position (6, 0, -3). The dynamic range of the irradiance profile over the coverage cell is 14.8 dB (maximum and minimum simulated irradiances are -32.2 dBm/cm^2 and -47.0 dBm/cm^2, respectively). As expected these results agree with the ones obtained through the theoretical model. This confirms that the simulation package is operating correctly.

3) - Simulation with optimization

As referred previously an array of 13 commercially available LEDs with two different HPBW values, emitting a total power of 152mW, would be required to illuminate the target cell. The resulting power distribution profile over the coverage cell is shown in figure 2.

This power distribution was achieved by using two arrays of LEDs with the following characteristics and orientation:

- 11 LEDs (P_t =12 mW and $HPBW$ =14°) with an elevation angle of 62° and uniformly distributed azimuthal angles, with one of the LEDs with an azimuthal angle of 0°.
- 2 LEDs (P_t =10 mW and $HPBW$ =55°) pointed down vertically (elevation angle of 0°).

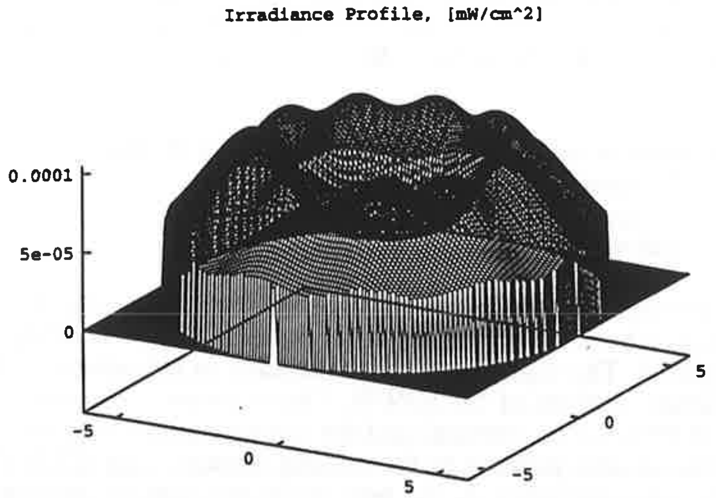

Figure 2 - Power density distribution profile with optimization.

The maximum channel propagation losses are now 65.2 dB/cm^2 at position (-6, 0, -3). Therefore there was a reduction of approximately 3.7 dB in the maximum channel losses. The dynamic range of the irradiance profile was also reduced to 3.3 dB (maximum and minimum irradiance are now -39.8 dBm/cm^2 and -43.1 dBm/cm^2, respectively). These values show the significant improvement that was obtained through the optimization process

B - System with Passive Reflection

This case is representative of indoor infrared systems where the ceiling surface presents good reflection characteristics. The stations are distributed over the room space and have the optical interfaces pointed vertically to the ceiling. The emitting station radiates the infrared signal towards the ceiling which is then reflected to the cell area. The main physical characteristics of the system we will consider for simulation are presented in table 2.

Parameter	Value
Room Length	24 m
Room Width	24 m
Room Height	4 m
Cell Radius	6 m
Resolution	20 cm
Ceiling Reflection Coefficient	0.8
Source Array	15 LEDs
Total Emitted Power	213 mW
Transceivers Plane	(x, y, -3)
Receiver Active Area	1.0 cm^2
Receiver Sensitivity	-46.1 dBm
Receiver *FOV*	85 degrees

Table 2 - Physical characteristics of a system with passive reflection.

The stations are considered to be distributed over a plane 1 meter above the floor. The cell is assumed circular and placed within a large open plant space. Thus, the reflections from the room walls can be neglected and only the reflections from the ceiling are considered. This represents a worst-case situation since the reflections from the room walls would increase the power collected by the stations.

We will consider three different variants of the system specified above:

- Non-optimized natural orientation.
- Non-optimized targeted orientation.
- Optimized natural orientation.

In the first case, the transceivers are assumed to be pointed vertically. In the second case the transceivers are assumed to be always pointing to the center of the cell ceiling. The results for both cases are shown in figure 3. The figure plots the irradiance as a function of the receiver position over the XX axis for several values of the *HPBW*. The non-optimized natural orientation case is labeled *vert* (LEDs and PINs on the vertical) and the non-optimized targeted orientation is labeled *align* (LEDs and PINs always pointed to the ceiling center). The *HPBW* correponds to the number in front of the previous label. In the non-optimized natural orientation case the power distribution has azimuthal symmetry. In the non-optimized targeted orientation case the power distribution is not symmetric but the worst case situation occurs in position (6, 0, -3) which is represented in the figure.

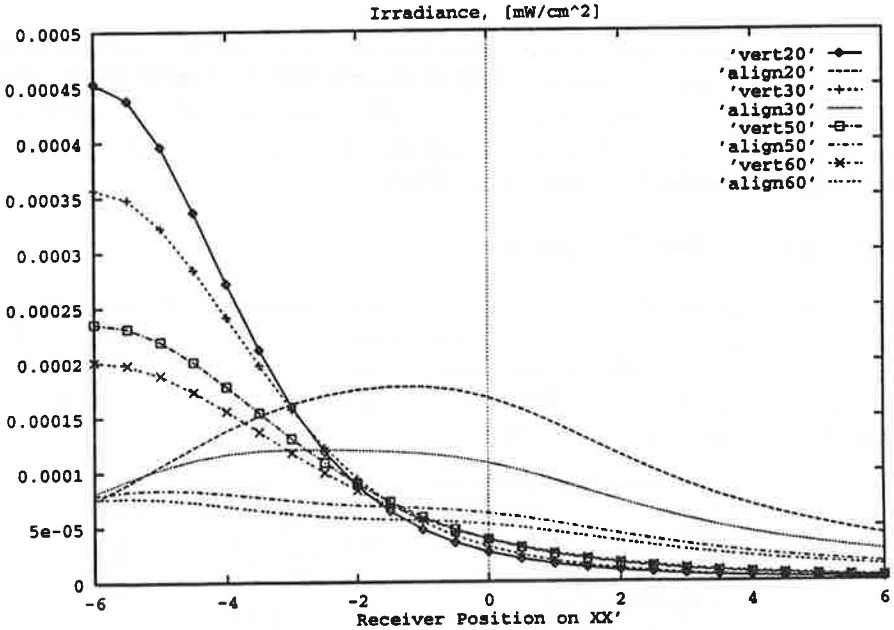

Figure 3 - Power density over the cell XX axis.

Figure 3 shows that the channel losses are smaller and the irradiance over the cell area is more uniform with targeted orientation. With natural orientation, the LEDs should have a wide *HPBW*. The best case in the figure corresponds to *HPBW*=60° which results in a maximum channel loss of 76.6 dB/cm^2. For the same LEDs the maximum channel losses with targeted orientation decreases to 71.8 dB/cm^2. The relative reduction in the channel losses would be even higher for systems using narrower LEDs.

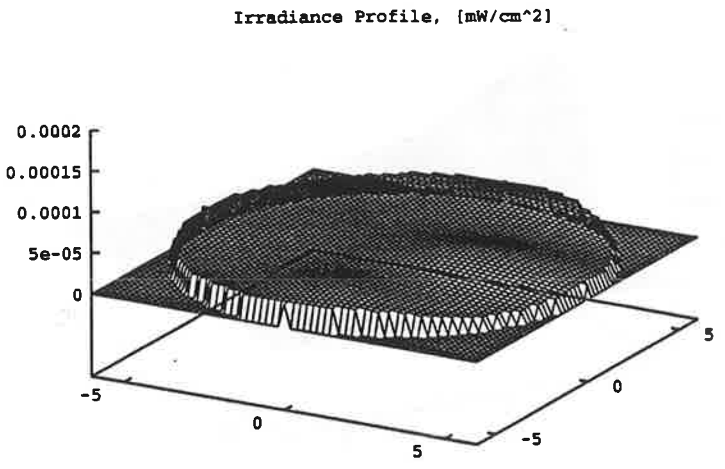

Figure 4 - Irradiance profile for natural orientation and optimization.

Targeted orientation is not practical from the users point of view. Thus, we will consider the case of natural orientation where the number, orientation and radiation pattern of the LEDs will be optimized in order to minimize the channel losses. The resulting power distribution profile over the cell area is shown in figure 4. This power distribution was achieved by considering two arrays of LEDs with the following characteristics and orientation:

- 11 LEDs (P_t=15 mW and *HPBW*=4.5°) with an elevation angle of 72° and uniformly distributed azimuthal angles, with one of the LEDs with an azimuthal angle of 0°.
- 4 LEDs (P_t=12 mW and *HPBW*=30°) with an elevation angle of 53° and uniformly distributed azimuthal angles, with one of the LEDs with an azimuthal angle of 0°

The maximum channel losses are now 71.6 dB/cm^2. A significant reduction in the power losses relative to the non-optimised case was achieved. In addition the maximum channel losses are lower than those obtained with targeted orientation.

Figures 5 and 6 show the irradiance profile over the cell area for the non-optimised cases previously discussed. As it can be seen, the power distribution of the optimized profile, Fig. 4, is significantly more uniform and the minimum irradiance is higher than on the non-optimized cases.

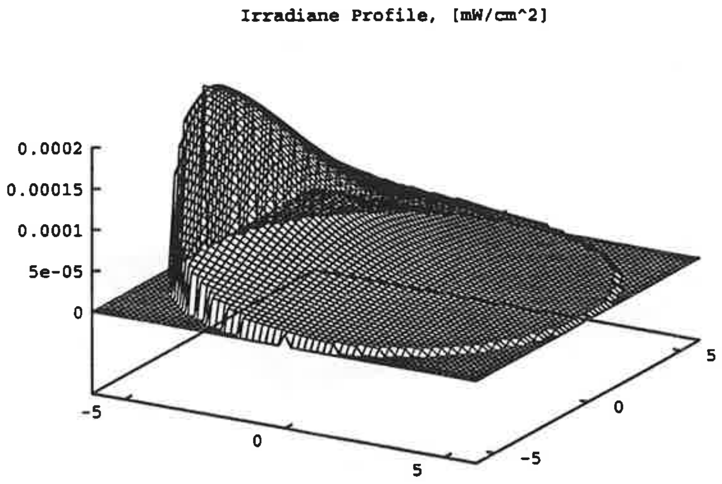

Figure 5 - Irradiance profile for non-optimized natural orientation.

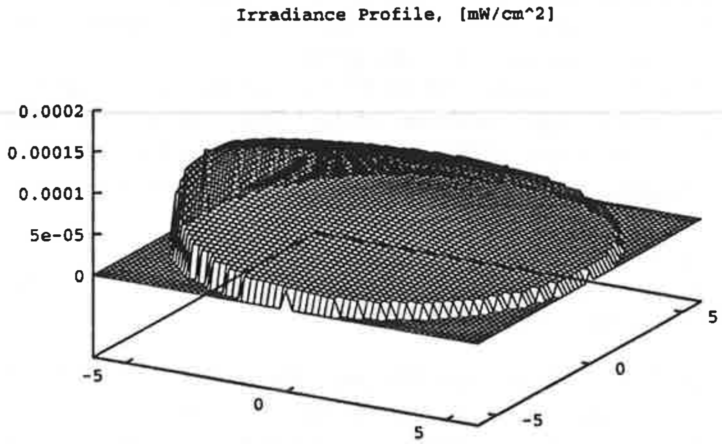

Figure 6 - Irradiance profile for non-optimized targeted orientation.

V - Conclusions and Future Work

Targeted orientation is advantageous over natural orientation but is not practical from the users point of view. Optimization of the power distribution profile can reduce the maximum channel propagation losses by several dBs. This improvement can be comparable to the achieved by targeted orientation of the transceivers.

To achieve a good improvement on the power distribution profile at least two types of LEDs are required. The LEDs with narrower *HPBW* should be pointed to the cell boundaries while the wider beam LEDs should be pointed to the cell center.

This package will be improved to evaluate the channel impulse response. The simulation package will be improved to include a model of the optical noise sources in order to evaluate the signal-to-noise ratio as a function of the receiver FOV. The inclusion of other reflection models in the simulation package is also under consideration.

Acknowledgments

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VI - References

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