Performance of wireless infrared transmission systems considering both ambient light interference and inter-symbol interference due to multipath dispersion

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ABSTRACT

The performance of optical wireless transmission systems is mainly impaired by the shot noise induced by ambient light, interference produced by artificial light sources, transmitted optical power limitations due to high path losses and channel bandwidth limitations due to inter-symbol interference (ISI) produced by the multipath dispersion of the optical signal. The contribution of these factors to the performance evaluation of infrared links have only been addressed independently and the combined effect of these channel impairments was not presented yet. The work presented in this paper extends the previous analysis by taking into account the combined effects of both optical noise (shot noise and interference) and channel impulse response. A simulation package was used to determine the indoor optical channel impulse response due to the propagation losses and multipath dispersion under various room geometries and emitter/receiver parameters. The contribution of the interference produced by incandescent and fluorescent lamps was done through the utilisation of analytical models. The penalty introduced by these channel characteristics was quantified considering the modulation schemes usually considered for optical wireless communication systems: 2-, 4- and 16-PPM (pulse position modulation) at bit rates from 1 to 10 *Mbps*.

Keywords: indoor infrared wireless communications, multipath dispersion, pulse position modulation, optical noise, optical interference, infrared.

1. INTRODUCTION

The utilisation of non-directed infrared (IR) radiation for indoor wireless local area networks was initially proposed by Gfeller[1]. Since then, an increasing number of contributions have presented on related subjects[2-16]. The demand of high data rate communications and user mobility, as well as the congested radio frequency (RF) spectrum, are increasing the investigation in this area. Since the communication channel is confined to closed rooms, the IR radiation has some advantages when compared to RF technology. The main advantages of the IR technology are the provision of an enormous unregulated bandwidth and the absence of interference generated communication users placed on adjacent rooms.

In spite of optical wireless communication is attractive for certain high-speed applications, there are several aspects which impair its performance. One of the most important aspects is the intersymbol interference (ISI) due to multipath dispersion[2-6]. The other important impairment for indoor infrared communication systems results from the strong interference induced by ambient light such as natural and man-made (artificial) light[1,5,7-12].

Non-directed infrared communication systems are mainly based on the following two configurations: i) line-of-sight (LOS) and ii) diffuse. These two types of links are illustrated in figure 1. A LOS link requires an unobstructed path for reliable communication whereas a diffuse link relies on the existence of surfaces with good reflection characteristics. LOS links require less optical power than diffuse links, but as diffuse links are more robust to shadowing we will consider both in our work. In both the LOS and diffuse links, the optical signal emanates from the transmitter and impinges the receiver after multiple reflections from walls and other reflectors. The multipath propagation causes a spread of the transmitted pulse, which results in ISI.

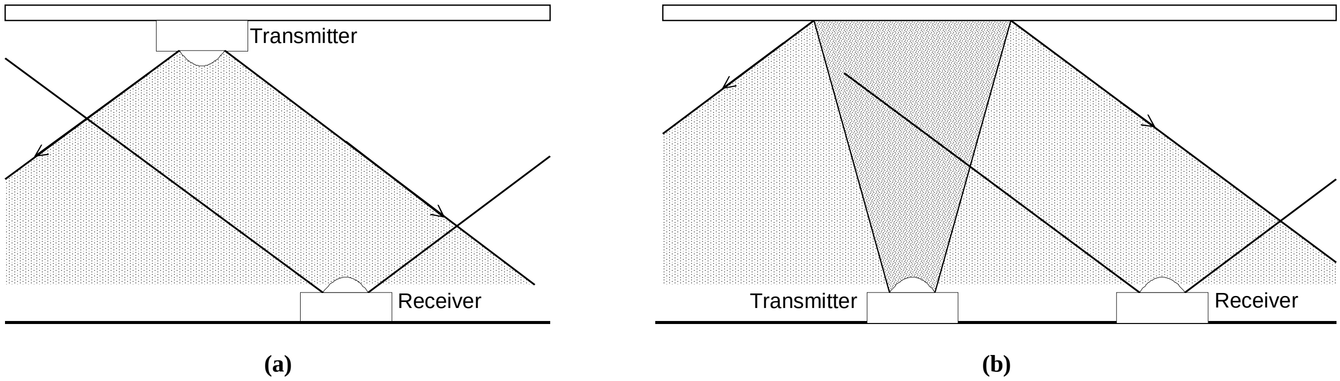


Figure 1. Configurations of non-directed indoor infrared links: **(a)** LOS, and **(b)** Diffuse.

The dominant source of noise in a non-directed link is background light, which is usually a combination of sunlight, incandescent and fluorescent light. The background light can be quite intense, especially near windows or under artificial light sources[7]. The background light induces a high intensity shot-noise in the photodetector. Artificial light sources are also responsible for an interfering noise into the optical front-end.

Since, the maximum optical power is limited by safety issues, high sensitivity modulation formats are desirable. The L-PPM modulation technique has been chosen because of its power and bandwidth efficiency[9,11,13,14]. Recent papers[9,11] examined the effects of artificial interference on PPM. We extend these results by examining the effects of both multipath ISI and optical interference induced by artificial light on L-PPM systems.

In this paper, the optical power penalty induced by both artificial light interference and ISI due to multipath dispersion in L-PPM wireless infrared transmission systems is evaluated. Section 2 describes the system model of the optical wireless communication system considered in our work. Section 3 presents the performance evaluation of an L-PPM system for a channel with artificial light interference and ISI due to multipath dispersion. In section 4, we present computed and simulated performance results. The main results of our work are presented in section 5.

2. SYSTEM MODEL

In this section we present the basic optical wireless communication system model. A schematic diagram for an optical wireless transmission system is illustrated in figure 2.

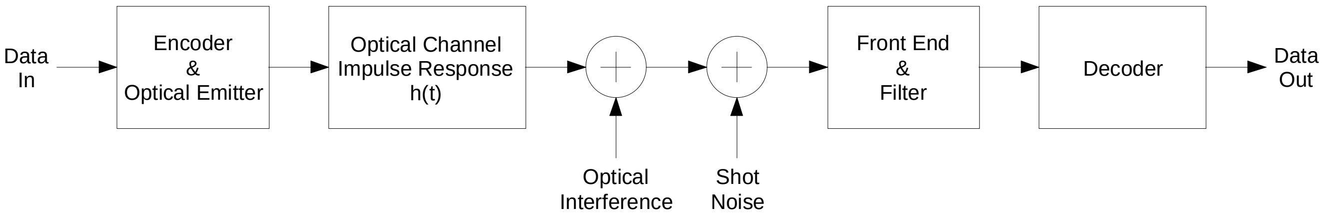


Figure 2. Block diagram of simulated infrared link using PPM with a MAP detector technique.

An optical wireless communication system is essentially composed by an encoder and an optical driver in the transmitter side and by an optical front-end and a decoder in the receiver. The main limitations of the optical channel are the multipath dispersion and the optical noise produced by natural and artificial light.

In a wireless infrared communication link, the existence of multiple paths between the transmitter and receiver ensures some resistance to shadowing of the receiver. However, it also causes temporal dispersion, which results from the multiple reflections of the optical signal on the walls, ceiling, floor and other objects. Multipath dispersion is the main bandwidth limitation of the communication system limiting the maximum data rate up to few tens of MHz[3,15,16].

The other main limitation of the optical wireless transmission systems is the noise and interference produced by the ambient light. Ambient light can be separated into two different classes: natural light (sunlight) and artificial light (incandescent and fluorescent). The optical light produced by these optical sources impinges the photodetector with high levels of irradiance and produces two types of noise: shot noise and interference. The average optical power (background power) that collides with the photodetector produces shot noise with mean square value proportional to the background optical power. Both natural and artificial light contribute to the shot noise, but the sun light is usually the most degrading factor[7]. The other limitation arises from the fast variations of the optical power produced by artificial light sources and causes interference, which is added to the transmitted signal.

There are, also, some limitations on the system performance due to the front-end noise. For a correct designed receiver the front-end noise (thermal noise and shot noise generated in the bipolar or FET transistors) is much lower than the shot noise due to the ambient light. Since we are interested to evaluate the performance of wireless infrared transmission systems considering both ambient light interference and ISI due to multipath dispersion, during this work, we made some assumptions to simplify the evaluation and the analysis of our work. So, our system model assumes that there are no bandwidth limitations imposed by the optical transmitter and by the optical front-end and that the receiver noise is negligible.

In this paper the system model presented in figure 2, assumes that there is a constant background natural light produced by the sunlight. Also, it is considered the contribution of the shot noise and interference noise due to three classes of artificial light sources: incandescent lamps, and fluorescent lamps driven by conventional or electronic ballasts. Finally, our model considers three propagation channels: i) an ideal distortion-free channel with no multipath dispersion, ii) a LOS propagation channel and iii) a diffuse propagation channel.

3. PERFORMANCE ANALYSIS

This section presents an analytical performance evaluation of an L-PPM system for a channel with artificial light interference and ISI due to multipath dispersion.

3.1 CHANNEL WITHOUT OPTICAL INTERFERENCE AND MULTIPATH DISPERSION FREE

In this paper we consider the PPM scheme using a Maximum-A-Posterior (MAP) detection and the required optical power is normalised to an NRZ-OOK reference system. This system considers a propagation channel without optical interference and multipath dispersion-free. In this section, the analytical models for the NRZ-OOK and L-PPM schemes are presented for a channel without multipath dispersion and interference but where background shot noise exists due to natural ambient light.

3.1.1 NRZ-OOK

In the absence of optical interference and multipath dispersion, assuming an integrate-and-dump filter in the receiver, considering equal probabilities for the possible transmitted bits "0" and "1" and presuming an optimal decision level, the bit-error-rate (BER) of the NRZ-OOK system is given by:

$$P_{e\_OOK} = \frac{1}{2} \cdot \mathrm{Erfc}\left(\frac{P_{avr} \cdot \Re \cdot \sqrt{T_b}}{\sqrt{2 \cdot q \cdot I_B}} \right) \tag{1}$$

where P_{avr} is the average received power, $\Re$ is the photodetector responsivity, T_b is the bit period, q is the electronic charge and I_B is the *DC* photocurrent due to the background ambient light.

3.1.2 L-PPM

In L-PPM systems the input bits, at bit rate $R_b = 1/T_b$, are converted in L-PPM symbols at rate $R_b / \log_2 L$. Each word of k input bits is mapped into one of the $L = 2^k$ possible symbols. An L-PPM symbol is composed by L consecutive time slots with duration $T_s = k \cdot T_b / L$, where one single slot has $L \cdot P_{avr} \cdot T_s$ energy and the other $L - 1$ slots have no energy.

The L-PPM system, considered under this work, assumes the utilisation of an integrate-and-dump (I&D) filter followed by a MAP detector. In a MAP detector, the received signal is sampled at every the L slots and the slot with the largest value is assigned to the right slot.

Following Moreira[9,13], for an L-PPM system using a MAP detector and considering no multipath dispersion and no optical interference, the bit error rate can be given by:

$$P_{e\_PPM} = \frac{L/2}{L-1} \cdot \left(1 - P_{SC}\right) \tag{2}$$

where P_{SC} is the probability of corrected detection of a symbol, and is given by:

$$P_{SC} = \frac{1}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} \exp\left(-x^2\right) \cdot \left[\frac{1}{2} \cdot \left(1 + \mathrm{Erf}\left(\frac{\sqrt{2} \cdot \sigma \cdot x + L \cdot P_{avr} \cdot \Re}{\sqrt{2} \cdot \sigma}\right)\right)\right] \tag{3}$$

and where $L \cdot P_{avr} \cdot \Re$ is the expected signal at the output of the I&D filter and σ is the shot noise root mean square value:

$$\sigma = \sqrt{q \cdot I_B / T_s} \tag{4}$$

3.2 CHANNEL WITH MULTIPATH DISPERSION

In this section we produce analytical models for the performance evaluation of an L-PPM system in presence of ISI due to multipath dispersion and consider only the background shot noise due to natural ambient light. Also, an I&D filter and a MAP detector technique are assumed. Results are presented later for three different propagation channels: (i) multipath dispersion-free (ii) LOS system and (iii) diffuse system.

In a wireless transmission system, the transmitted signal is passed through the multipath channel and for fixed transmitter and receiver locations, multipath dispersion is completely characterised by an impulse response $h(t)$. The impulse response can be used to analyse or simulate the effects of multipath dispersion on indoor optical communication systems. We assume, in this section, that $h(t)$ is normalised to have unity area so that $H(0) = 1$ and that the received signal plus noise is passed through an integrate and dump filter.

For an L-PPM system corrupted by multipath dispersion, equation (2) is rewritten to account the ISI contribution. So, for an L-PPM system using a MAP detector, considering multipath dispersion and assuming that the impulse response spans over M symbols, the bit error rate can be given by:

$$P_{e\_PPM_{MD}} = \frac{L/2}{L-1} \cdot \left(1 - P_{SC_{MD}}\right) \tag{5}$$

where $P_{SC_{MD}}$ is the probability of the correct detection of a symbol, considering the ISI due to multipath dispersion, and is given by:

$$P_{SC_{MD}} = \frac{1}{L^{M+1} \cdot \sqrt{\pi}} \sum_{\mathbf{W}} \sum_{k=1}^{L} \left(\int_{-\infty}^{\infty} \exp\left(-x^2\right) \cdot \left(\prod_{\substack{j=1 \\ j \neq k}}^{L} \frac{1}{2} \cdot \left(1 + \mathrm{Erf}\left(\Phi_{k,j}(x)\right)\right) \right) \cdot dx \right) \tag{6}$$

with:

$$\Phi_{k,j}(x) = \frac{\sqrt{2} \cdot \sigma \cdot x + L \cdot P_{avr} \cdot \Re \cdot (c_k - c_j)}{\sqrt{2} \cdot \sigma} \tag{7}$$

where the first summation of equation (6) is over all $\mathbf{W} \in C^M$, where C is the set of L valid codewords. $M+1$ is the number of L-PPM symbols with non-zero terms due to the impulse response, c_k is the expected impulse response contribution after the I&D filter at the sampling time for the k^{th} slot assuming that a pulse was transmitted in that slot and c_j is the expected impulse response contribution after the I&D filter at the sampling time for the j slots which are the non-energy slots.

3.3 CHANNEL WITH ARTIFICIAL LIGHT INTERFERENCE

In this section we consider an L-PPM system using a MAP detector under artificial and natural ambient light conditions. The work presented by Moreira[8] described the optical interference into three different classes accordingly to its source: incandescent light, fluorescent light and fluorescent light driven by electronic ballasts. We have performed A detailed analytical analysis[9,13] has been performed for L-PPM systems under artificial light sources, which is followed during this work. The analysis, here presented, is developed independently of the artificial light source. Some results are presented in a later section for the three types of optical interference.

The artificial light sources produce a background light which induce a *DC* photocurrent into the photodetector causing a stationary quantum noise, usually referred as shot noise. Also, the artificial light sources generate an undesired interference noise. So, in the case of an optical transmission system under artificial light, the shot noise mean square value is obtained through a simple changing of equation (4) and is given by:

$$\sigma_T^2 = q \cdot \left(I_{B_N} + I_{B_A}\right) / T_s \tag{8}$$

where I_{B_N} and I_{B_A} are the *DC* induced photocurrents due to natural and artificial light sources, respectively. The value of the interference at the output of the I&D filter is given by:

$$v_i(t) = \int_{t-T}^{t} i_{interf}(t') \cdot dt' \tag{9}$$

where $i_{interf}(t')$ is the interference induced current into the photodetector[8] and T is the duration of the integration which corresponds to the time slot duration (T_s) of an L-PPM symbol.

For an L-PPM system using a MAP detector and considering both background shot noise and optical interference, the bit error rate is given by[13]:

$$P_{e\_PPM_I} = \frac{L/2}{L-1} \cdot \left(1 - \frac{1}{T_i} \int_{t_0}^{t_0+T_i} P_{SC_I}(\mathbf{V}(t)) \cdot dt\right) \tag{10}$$

where T_i is the period of the interference and $\mathbf{V}(t)$ is a vector with the value of the interference at the sampling time for L consecutive time slots:

$$\mathbf{V}(t) = \{v_i(t), v_i(t+T_s), v_i(t+2 \cdot T_s), \ldots, v_i(t+(L-1) \cdot T_s)\} \tag{11}$$

and the probability of corrected detection of a symbol considering the optical interference, $P_{SC_I}(\mathbf{V}(t))$, is given by:

$$P_{SC_I}(\mathbf{V}(t)) = \frac{1}{L\cdot\sqrt{\pi}}\cdot\sum_{k=1}^{L}\left(\int_{-\infty}^{\infty}\exp\left(-x^2\right)\cdot\left(\prod_{\substack{j=1\\ j\neq k}}^{L}\frac{1}{2}\cdot\left(1+\mathrm{Erf}\left(\Lambda_{k,j}(x)\right)\right)\right)\cdot dx\right) \tag{12}$$

with:

$$\Lambda_{k,j}(x) = \frac{\sqrt{2}\cdot\sigma\cdot x + L\cdot P_{avr}\cdot\Re + \mathbf{V}_k - \mathbf{V}_j}{\sqrt{2}\cdot\sigma_T} \tag{13}$$

3.4 CHANNEL WITH MULTIPATH DISPERSION AND OPTICAL INTERFERENCE

In this section we evaluate the system performance of an L-PPM infrared transmission system in presence of background natural and artificial ambient light, optical interference due artificial light and ISI due to multipath dispersion. Similarly to section 3.2, in this section we use the impulse response, achieved through simulation, to consider the contribution of the ISI due to multipath dispersion into the infrared system performance.

Also in this section, an I&D filter and a MAP detector are considered in our system. Results are presented later for three different propagation channels (multipath dispersion-free, LOS and diffuse) and considering three types of optical interference (incandescent light and fluorescent light driven by a conventional ballast and by an electronic ballast). Under these channel conditions, we assume that the impulse response spans over M symbols and that the shot noise mean square value, σ_T^2, is given by equation (8). The value of the interference at the output of the I&D filter is given by equation (9). So, for an L-PPM system using a MAP detector and considering the ISI due to multipath dispersion, shot noise due to background light and optical interference due to artificial light, the bit error rate is given by:

$$P_{e\_PPM_{I\_MD}} = \frac{L/2}{L-1}\cdot\left(1-\frac{1}{T_i}\int_{t_0}^{t_0+T_i}P_{SC_{I\_MD}}(\mathbf{V}(t))\cdot dt\right) \tag{14}$$

where $\mathbf{V}(t)$ a vector with the value of the interference at the sampling time for L consecutive time slots and is given by equation (11). The probability of a corrected detection of a symbol considering both the multipath dispersion and optical interference, $P_{SC_{I\_MD}}(\mathbf{V}(t))$, is given by:

$$P_{SC_{I\_MD}} = \frac{1}{L^{M+1}\cdot\sqrt{\pi}}\sum_{\mathbf{W}}\sum_{k=1}^{L}\left(\int_{-\infty}^{\infty}\exp\left(-x^2\right)\cdot\left(\prod_{\substack{j=1\\ j\neq k}}^{L}\frac{1}{2}\cdot\left(1+\mathrm{Erf}\left(\Psi_{k,j}(x)\right)\right)\right)\cdot dx\right) \tag{15}$$

with

$$\Psi_{k,j}(x) = \frac{\sqrt{2}\cdot\sigma\cdot x + L\cdot P_{avr}\cdot\Re\cdot\left(c_k - c_j\right) + \mathbf{V}_k - \mathbf{V}_j}{\sqrt{2}\cdot\sigma_T} \tag{16}$$

4. MAIN RESULTS

In this section we present the main results of the bit error rate versus the required optical power for L-PPM systems under several channel propagation characteristics. The required optical power is normalised to an NRZ-OOK reference system considering a channel with no optical interference and no multipath ISI. We define an optical power penalty as the increased optical signal power required to overcome the optical channel impairments (multipath ISI and optical interference) and to achieve BER = 10^{-5}.

$$P = 10 \cdot \log_{10}\left(\frac{\text{Extra optical signal required for L - PPM system (BER} = 10^{-5}\text{) with ISI and/or optical interference}}{\text{Optical signal required for NRZ - OOK system at 1 Mbps (BER} = 10^{-5}\text{) without ISI and optical interference}} \right) \tag{17}$$

The performance of wireless infrared systems is greatly dependent on the channel characteristics. The results presented in this section are only a few examples of the large set of the possible room configurations, receiver and emitter locations, number and type of lighting devices, etc. As we referred during this paper, we consider in our study four ambient light conditions and three propagation channels. The ambient light conditions considered in our study are:

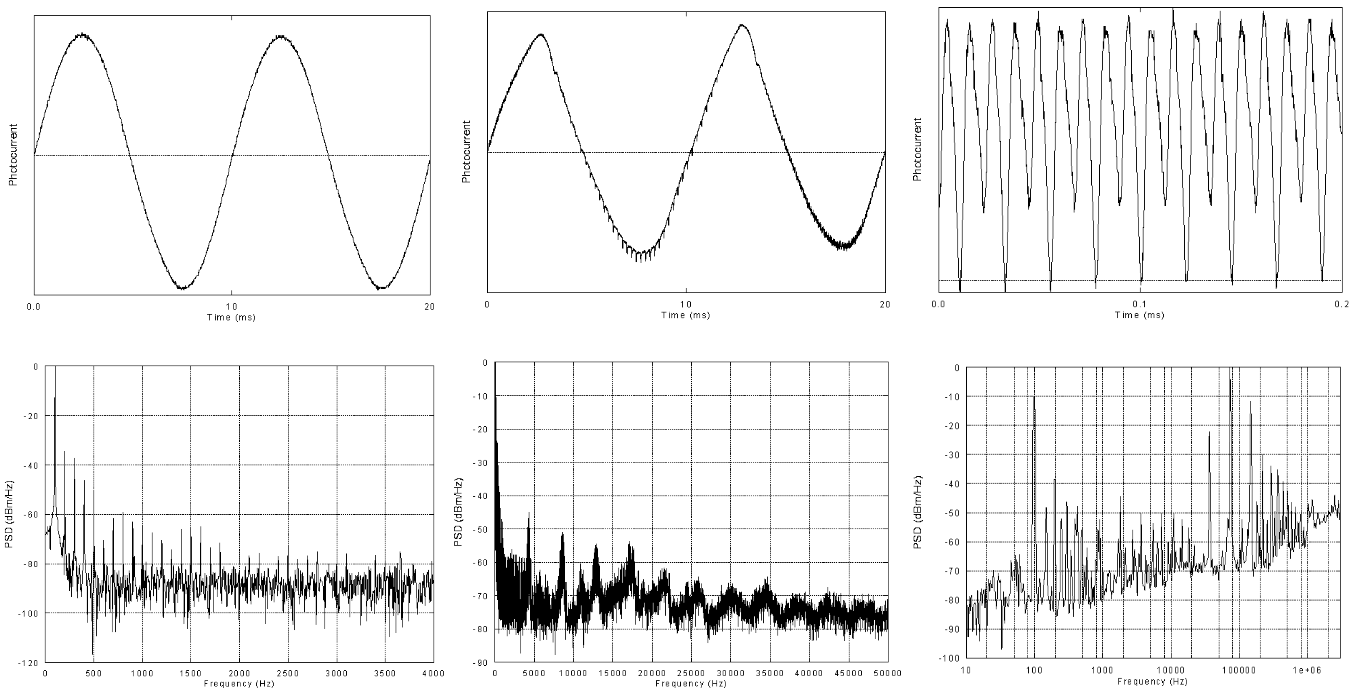
Case A - No optical interference: Natural (sun) light ($I_{B_N} = 200\mu A$);

Case B - Incandescent interference: Sunlight ($I_{B_N} = 200\mu A$) and a 60 *W* incandescent lamp placed 1 meter away from the receiver ($I_{B_A} = 56\mu A$);

Case C - Fluorescent interference (conventional ballast): Sunlight ($I_{B_N} = 200\mu A$) and eight 36 *W* fluorescent lamps driven by conventional ballasts in a 5 $m \times 6$ m room with the receiver placed under one illumination unit, 2.2 *m* away ($I_{B_A} = 2\mu A$);

Case D - Fluorescent interference (electronic ballast): Identical to case C, but with fluorescent lamps driven by electronic ballasts $I_{B_A} = 2\mu A$.

For the evaluation of the optical power penalty due to artificial light sources, we use the optical interference models obtained from experimental characterisations[8,13] of the optical interference. The interference waveforms and power spectral density (PSD), for the three types of artificial light sources, considered in our study, are presented in figure 3.



(a) **(b)** **(c)**

Figure 3. Photocurrent waveforms (the dc components of the waveforms was removed) and PSD:
(a) Incandescent lamp (Case B); **(b)** Fluorescent lamps (Case C);
(c) Fluorescent lamps driven by electronic ballasts (Case D).

The electrical signal interference produced by the incandescent lamp (case B) is close to a sinusoid and the electrical power spectrum extends up to 1 *kHz*. For the fluorescent lamp driven by conventional ballast (case C) the electrical power spectrum extends up to 20 *kHz*. For the fluorescent lamp driven by electronic ballast (case D), the electrical power spectrum of the optical interference has significant frequency components up to 1 *MHz*.

For the evaluation of the optical penalty induced by the propagation channel characteristics we use the impulse response obtained through simulation using the SCOPE simulation package[6]. The analyses was extended up to three different cases corresponding to:

Case I - No multipath dispersion;

Case II - Line-of-sight configuration;

Case III - Diffuse configuration.

The optical channel impulse response and the corresponding magnitude response were obtained through detailed numerical simulation of optical propagation, including reflections up to fifth order[6]. Figure 4 presents the results obtained for two particular emitter and receiver positions in a 12 $m \times 12\ m \times 4\ m$ (length $\times$ width $\times$ height) room having highly reflective walls and ceiling ($\rho_{ceiling} = \rho_{walls} = 0.8$ and $\rho_{floor} = 0.3$). Both configurations consider an ideal Lambertian transmitter (half power angle = 60°) emitting 1 *W* optical power. Also, for the two cases, the receiver has an active area of 1 cm^2 and a field of view of 85°. Case II represents a LOS system with the receiver placed 1 meter above the floor at the position (5.0, 3.4, -3.0) and the emitter placed on the ceiling centre (xyz axis reference) and pointing straight down. In this case the LOS pulse arrives with a propagation delay of 22.6 *ns* and carries 38% of the optical power received up to the fifth reflection. Case III represents a diffuse system with the transmitter in the centre of the room, placed 1 meter above the floor and straight up oriented. In this case the receiver is placed at the same place as in the previous one.

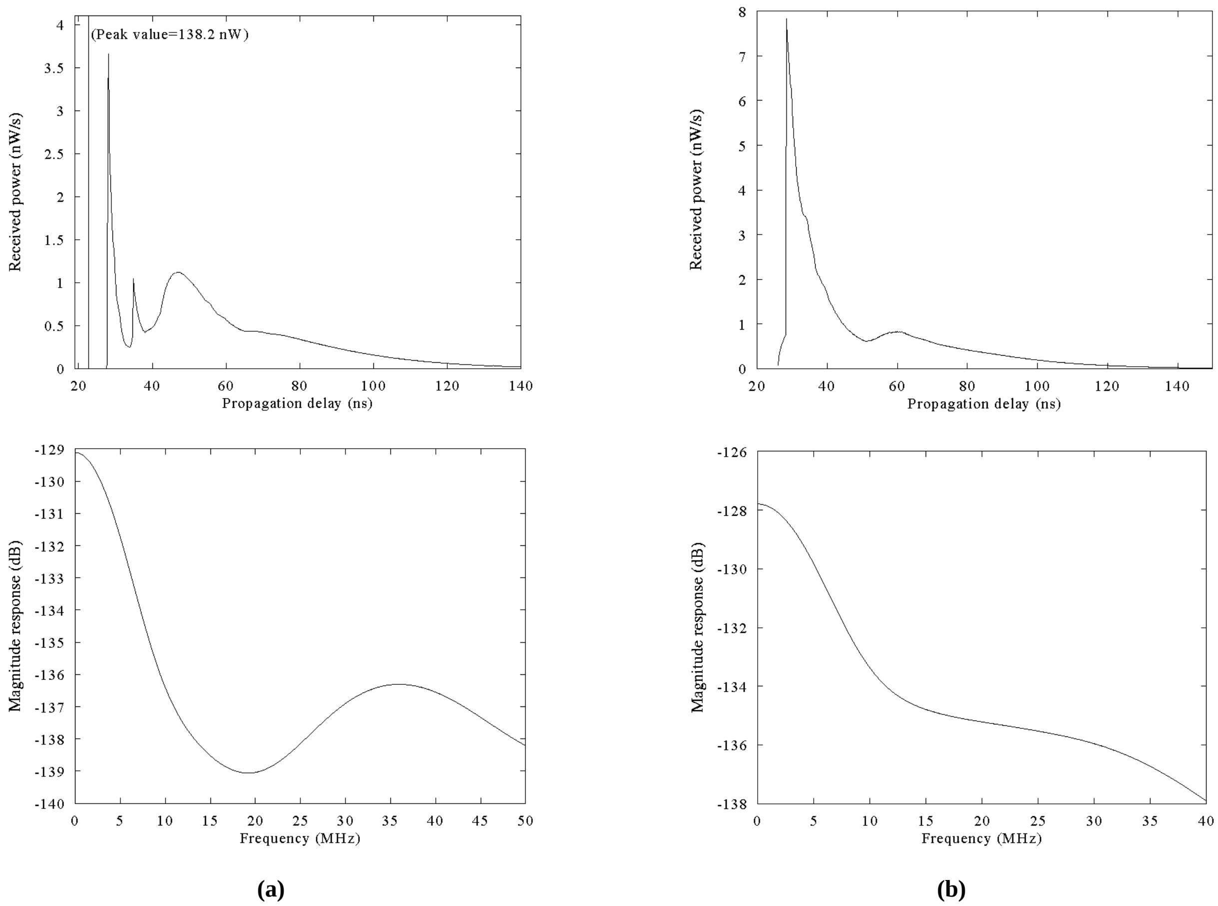


Figure 4. Optical channel impulse response and magnitude response for a: **(a)** line-of-sight system (Case II); **(b)** diffuse system (Case III).

During the evaluation of the L-PPM system performance we used artificial light interference models[8,13] for the artificial light sources presented in figure 3. We employ, also, the impulse response results for LOS and diffuse channels presented in figure 4. Because we have considered a lot of cases, we present, only, the main curves of the BER-vs.-SNR performance of L-PPM links subject to both artificial light and multipath dispersion. At the end of this section we summarise the penalty due to these impairments for the all cases considered in this work.

Among typically used artificial light sources, the optical interference induced by fluorescent lamps driven by electronic ballasts has been presented as the major impairment when compared to the other classes of light sources. For this reason, we focus the discussion of the achieved results to case D (fluorescent lamps driven by electronic ballasts). Figure 5 illustrates an example of the BER-vs.-SNR performance of 1 *Mpbs* links subject to fluorescent light interference induced by fluorescent lamps driven by electronic ballasts and considers a diffuse propagation system. Also, there are some curves for 1 *Mbps* links with no artificial light source and/or multipath ISI. From figure 5, it is shown that 16-PPM is identified as the better solution for all cases considered. An important remark obtained from the figure is that the penalty induced by ISI interference due to the multipath dispersion for case III (diffuse) is very small (about 0.4 *dB* for all orders of PPM) when compared to the penalty induced by the artificial interference, which varies from about 9 *dB* to about 14 *dB*.

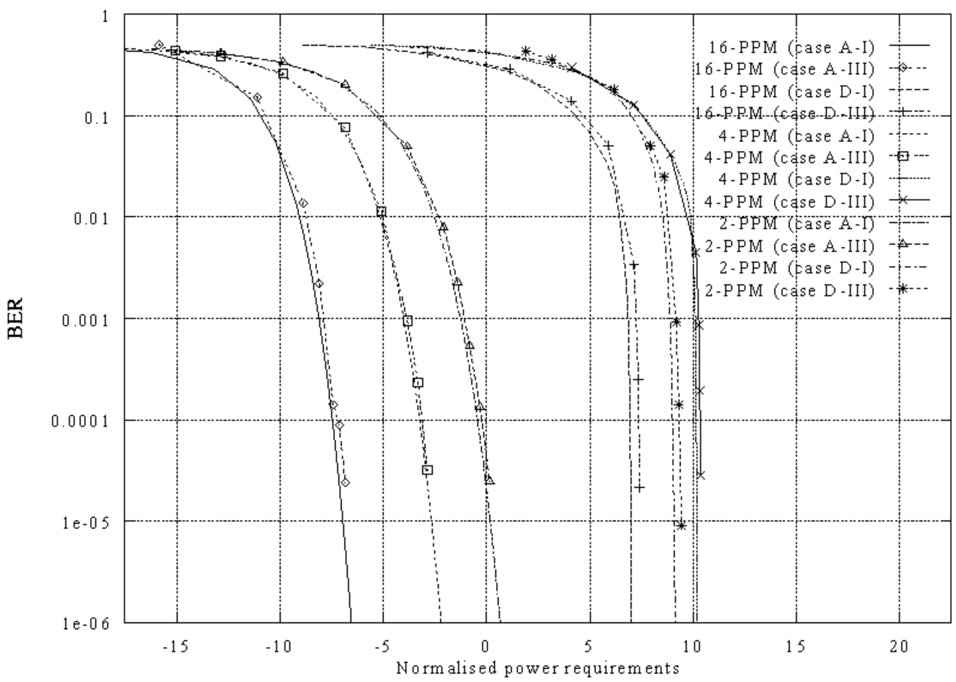


Figure 5. Penalty induced by artificial light interference and ISI due to multipath dispersion in a 1 *Mbps* L-PPM system.

In figure 6, we verify, that for a diffuse system operating at 10 *Mbps*, multipath ISI is the main degrading factor of the system performance. Indeed, for this system the penalty induced by multipath ISI is about 10 *dB* for all orders of PPM when no artificial interference is present. When we analyse the system performance under both degrading factors, the penalty induced by multipath dispersion is greater for 2-PPM than for 16-PPM. Also, it is verified that for 10 *Mbps* the penalty induced by fluorescent lamps driven by electronic ballasts is much smaller than the penalty provoked by the multipath dispersion. For these channel conditions, 4-PPM is the best choice modulation method. In fact, the normalised optical power required for 16-PPM is about 0.7 *dB* larger than for 4-PPM when considering both the channel impairments.

In figure 7 we present the bit error rate results for a non-directed LOS system considering both multipath ISI and artificial interference induced by fluorescent lamps driven by electronic ballasts. It is shown that for all channel conditions considered in this figure, 16-PPM proves to be the best choice. When only multipath ISI due to the LOS link is considered the optical power required for 16-PPM is about 3.3 *dB* smaller than for 4-PPM. When both the multipath ISI and optical interference are considered, the excess of required optical power for 4-PPM over 16-PPM reduces to about 2.3 dB, but even in this case the 16-PPM modulation method remains the best choice.

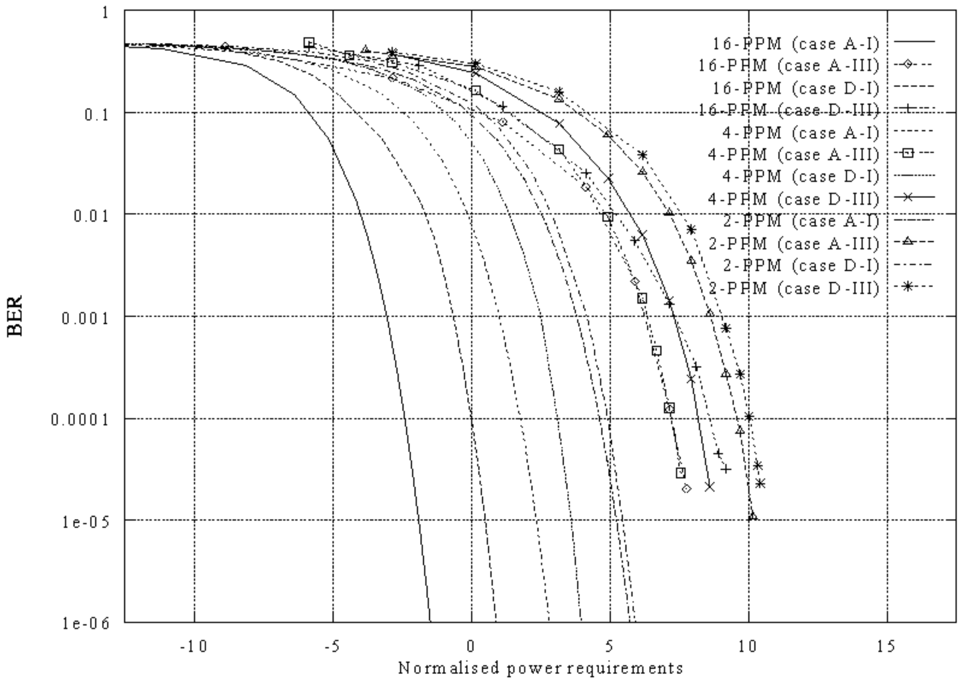


Figure 6. Penalty induced by fluorescent light driven by electronic ballast and multipath ISI (diffuse link) in a 10 *Mbps* L-PPM system.

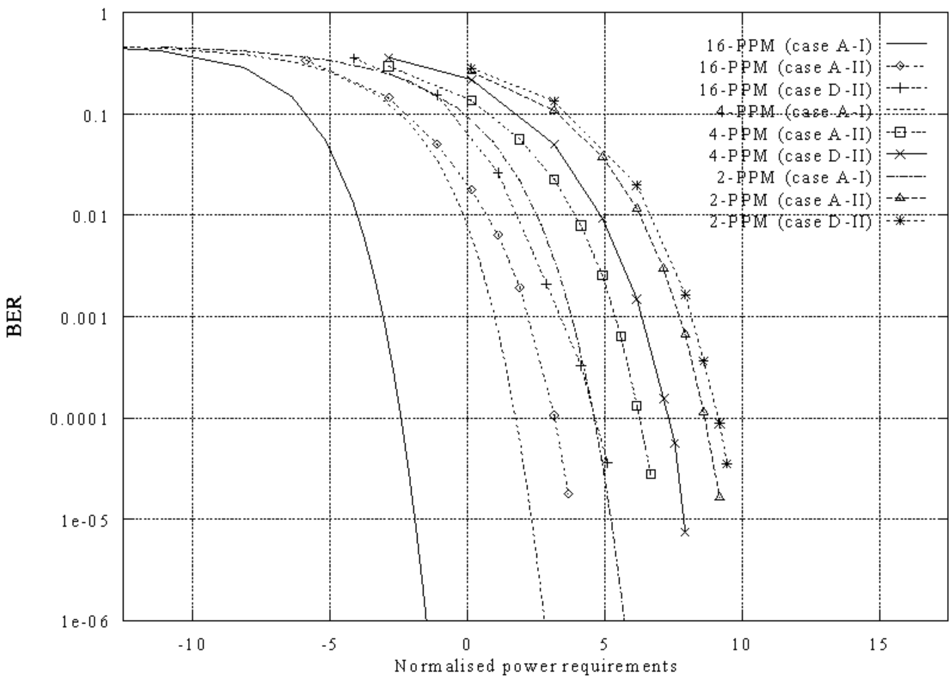


Figure 7. Penalty induced by fluorescent light driven by electronic ballast and multipath ISI (LOS link) in a 10 *Mbps* L-PPM system.

Table 1 summarises the results obtained for the required optical power for all the channel conditions considered in this work. The required optical power is normalised to a reference system as defined by equation (17). From the table we can see that, for 1 *Mbps*, 16-PPM links have the smallest optical power requirements. For 10 *Mbps* systems, 16-PPM still requires the smallest amount of optical power, except for the case III (diffuse system) where 4-PPM modulation method has better results.

		Propagation Channel	Ambient Light Conditions			
			Case A	Case B	Case C	Case D
1 *Mbps*	16-PPM	Case I	-7.1	-6.3	-6.8	+7.0
		Case II (LOS)	-6.7	-6.0	-6.6	+7.4
		Case III (DIF)	-6.6	-6.0	-6.5	+7.4
	4-PPM	Case I	-2.9	-2.2	-2.8	+10.1
		Case II (LOS)	-2.7	-2.0	-2.6	+10.4
		Case III (DIF)	-2.6	-2.0	-2.5	+10.4
	2-PPM	Case I	+0.1	+0.6	+0.1	+9.0
		Case II (LOS)	+0.5	+1.0	+0.5	+9.4
		Case III (DIF)	+0.5	+1.0	+0.5	+9.4
10 *Mbps*	16-PPM	Case I	-1.9	-1.5	-1.8	+0.4
		Case II (LOS)	+3.8	+4.3	+4.0	+5.5
		Case III (DIF)	+8.0	+8.6	+8.2	+9.5
	4-PPM	Case I	+2.2	+2.7	+2.3	+3.6
		Case II (LOS)	+7.1	+7.6	+7.2	+7.8
		Case III (DIF)	+7.9	+8.4	+8.0	+8.8
	2-PPM	Case I	+5.1	+5.6	+5.2	+5.5
		Case II (LOS)	+9.4	+9.9	+9.5	+9.8
		Case III (DIF)	+10.2	+10.7	+10.3	+10.6

Table 1. Required optical power for an L-PPM system at 1 and 10 *Mbps* ($BER_0 = 10^{-5}$).

5. CONCLUSIONS

Using analytical models for the artificial interference and channel impulse response obtained through simulation, we have evaluated the performance of L-PPM infrared links in presence of both these channel impairments.

For 1 Mbps communication systems corrupted by both artificial interference and multipath ISI due to multipath dispersion, 16-PPM modulation scheme showed to have the best power-bandwidth efficiency. When a 10 Mbps system was considered, for an ideal ISI-free channel, 16-PPM requires the smallest optical power among all the schemes evaluated. Even for the non-directed LOS link 16-PPM showed to be the best choice under all the interfering artificial light sources. For the case of a diffuse ISI channel, 4-PPM requires about 0.7 *dB* less optical power than does 16-PPM.

It was verified that for L-PPM systems with MAP detection, the required optical power for 1 *Mbps* communication systems is mainly imposed by artificial and natural light sources. For 10 *Mbps* systems, the major degrading factor of the system performance is the multipath ISI, especially for diffuse systems. As a final remark, the optical interference due to artificial light is much more important for low data rate systems while ISI is the most significant factor for high data rates.

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