Characterisation and Modelling of Artificial Light Interference in Optical Wireless Communication Systems

Adriano J. C. Moreira, Rui T. Valadas, A. M. de Oliveira Duarte

Dept. de Electrónica e Telecomunicações, Universidade de Aveiro
3810 Aveiro, Portugal
Tel: +351 34 381937, Fax: +351 34 381941, Email: adriano@ci.ua.pt

ABSTRACT *Wireless indoor infrared transmission systems are affected by noise and interference induced by natural and artificial ambient light. While the shot noise induced on the receiver photodiode by steady ambient light has been extensively described and included in system models, the interference produced by artificial light has only been mentioned as a source of degradation and quite simple descriptions have been presented.*

This paper presents a characterisation (through extensive measurements) of the interference produced by artificial light and proposes a simple model to describe it. These measurements show that artificial light can introduce significant in-band components for systems operating at bit rates up to several Mbit/s. Therefore it is essential to include it as part of the optical wireless indoor channel.

The measurements show that fluorescent lamps driven by solid state ballasts produce the wider band interfering signals, and are then expected to be the more important source of degradation in optical wireless systems.(*)

Introduction

Wireless indoor infrared transmissions systems have been widely considered as part of a panoply of communication systems, the most important being the wireless LANs [1, 2].

The performance of wireless infrared systems is limited by several aspects, the most important being: the speed limitations of the optoelectronic devices (LEDs and PIN photodiodes); the significant high path loss which leads to the use of considerably high optical power levels; multi-path dispersion; the receiver noise; the shot noise induced by natural and artificial light on the receiving photodiode and the interference induced by artificial light. Most of these aspects have been considered in the performance analysis of wireless infrared systems and, in particular, spatial distributions for the average shot noise levels within rooms have been presented recently [10]. However, the interference induced by artificial illuminating devices, despite of being referred by several authors [1, 2, 4], has not been included in the system models. It is usually assumed that this kind of interference imposes some amount of optical power penalty but this has not been explicitly included in the system performance calculations. In practical implementations, this interfering signal is usually filtered out using electrical high-pass filters and no penalty is assigned to this signal processing operation.

In this paper the interference induced by artificial light is characterised through extensive measurements and a simple model to describe it is proposed. Techniques to estimate the model parameters and some typical values are also presented. The new model can be used to estimate the optical power penalty induced by this type of interference in optical wireless communication systems. This model will allow the performance re-evaluation of the several modulation methods being proposed for optical wireless systems [2,3-6] and based on those results new techniques may have to be studied.

Section A of this paper presents the experimental results. These were grouped accordingly to their major characteristics to produce classes of typical ambient light sources.

Section B proposes a simple model to describe both the steady ambient light levels and the interfering signals, suitable to be used to estimate the penalties induced in transmission systems. The conclusions are presented in section C.

A. Ambient Light Characterisation

Natural and artificial light sources produce a certain amount of background optical power density or irradiance that impairs the optical receivers performance. The effects of this background irradiance manifests in two distinct forms: as shot noise induced on the receiver photodiode by the steady background irradiance and as interference induced by the variations in time of the same irradiance. The relationship between these two components is described in section B.

For the characterisation of both the noise and interference produced by ambient light, several light sources have been considered: sun light, incandescent lamps with tungsten filament, fluorescent lamps driven by conventional ballasts and fluorescent lamps geared by electronic ballasts. While the background irradiance produced by sun light can be considered steady with slow intensity variations in time, most of them due to shadowing, artificial light exhibit large and fast intensity variations in time which produces an interfering signal on the infrared receiver. This way, both types of light

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sources (natural and artificial) contribute to the generation of shot noise on the receiver photodiode while only the artificial light sources generate interference.

The experimental results presented in this section represent average values obtained from measurements over six incandescent lamps, nine fluorescent lamps, two of them with incorporated electronic ballasts, two conventional ballasts and three other electronic ballasts. The devices population was chosen from the most used types of artificial light sources and its extent was determined by the availability of real different types.

A1. Shot noise

The steady background irradiance produced by natural and artificial light sources is usually characterised by the d.c. current it induces on the receiver photodiode since the resulting shot noise power is directly proportional to that current [9]. This current is usually referred as the background current (I_B) [1]. This parameter can be easily included in the system models to account for the shot noise produced by the background light.

This background irradiance was measured for several typical ambient light conditions and the corresponding background current values (I_B) are presented in table 1. This experiment was performed by measuring the current induced on a 0.85 cm^2 silicon PIN photodiode. Two types of measurements were performed: without any kind of optical filter and using a long-pass absorption optical filter with cut-off wavelength at 800 nm. The measurements were performed for several ambient light conditions from which those in table 1 are the most representative. The sun light measurements were performed on a very shiny day; the values presented for incandescent light correspond to the irradiance produced by a 60 W lamp placed 1 meter away from the photodiode; the fluorescent light measurements were performed within a well illuminated room (8×36W lamps in a 5×6m room) with the photodiode pointing to the ceiling and under one pair of lamps, placed 2.2 m away. The background current produced by conventional fluorescent lamps and those driven by electronic ballasts is similar: the advantages of electronic driven lamps are mainly the lower electrical power consumption, shorter start-up time, longer life-time and flicker free operation.

	Without optical filter	With optical filter	Optical filter reduction
Direct sun light	5100 uA	1000 uA	5.1
Indirect sun light	740 uA	190 uA	3.9
Incandescent light	84 uA	56 uA	1.5
Fluorescent light	40 uA	2 uA	20

Table 1. Background current (IB) for several illumination conditions.

While similar results have already been presented [4], they are presented here again for two distinct reasons:

a) these values can be used latter for system performance calculations;

b) it will be shown that there is a close relationship between the steady ambient light level produced by artificial light sources and the corresponding interference amplitude.

From table 1 it is clear that sun light produces the higher levels of background current and it is therefore the major source of shot noise on the receiver photodiode. Table 1 also shows that, in a well naturally illuminated room, the background current can be as high as 5 mA under direct sun light while for a well artificial illuminated room it should not be higher than a few tens of μA. This is a very important aspect to consider on system design since optical receivers should be able to deal with a wide range of steady background light levels.

Another important conclusion arising from table 1 is that optical filtering greatly reduces the background current. The higher gains are achieved for fluorescent light while the lower gains are for incandescent light. This is due to the differences in the optical spectrum of each light source [1, 5].

Much higher levels of attenuation on the I_B current can be achieved if interference optical filters are used. However, the current high cost of these devices makes its use on low-cost systems prohibitive.

A2. Interference

Today illuminating devices make use of a large number of different light sources such as incandescent lamps with tungsten filaments, halogen and mercury lamps, fluorescent lamps with different emitting colour (optical spectra) and, more recently, fluorescent lamps geared by electronics ballasts. Each of these light sources present particular characteristics, advantages and drawbacks in terms of their capabilities to illuminate a particular site.

A large number of those light sources have been tested in terms of the interference each one of them induces in wireless infrared systems, and it was found that they can be grouped into three categories or classes accordingly to their effects:

a) incandescent lamps (including halogen lamps);
b) fluorescent lamps equipped with conventional ballasts;
c) fluorescent lamps equipped with electronic ballasts.

The results presented in this section latter on, will show that the characteristics of the interference produced by each of this category of light sources are very similar.

A2.1. Measurement setup

In order to measure the interfering signal produced by each of the light sources, a differential optical receiver was used [11]. The receiver presents a flat frequency response between 10 Hz and about 3 MHz and a transimpedance gain of 1.1 Mohm.

Two silicon PIN photodiodes with 1.7 cm^2 of total active area, peak responsivity at 900 nm and 0.6 of responsivity were used. Since this is the most commonly used type of photodiode for wireless infrared applications, the achieved results can be considered to be of general applicability.

The interference measurements were performed both in the time and frequency domains, using a fast sampling rate digital storage oscilloscope capable of transient acquisition and a spectrum analyser with operating range from 1 Hz to 500 MHz and high frequency resolution.
All measurements were performed with the receiver photodiode pointing directly to the lamp.

A2.2. Incandescent lamps

Six different types of incandescent lamps were tested and they all presented similar characteristics in terms of the produced interference. Halogen lamps were also tested leading to similar results, except that, for the same electrical power, they produce more intense irradiation levels that conventional incandescent lamps. The electrical spectrum of the interfering signal produced by a 60W incandescent lamp with tungsten filament is shown in figure 1. No optical filters have been used.

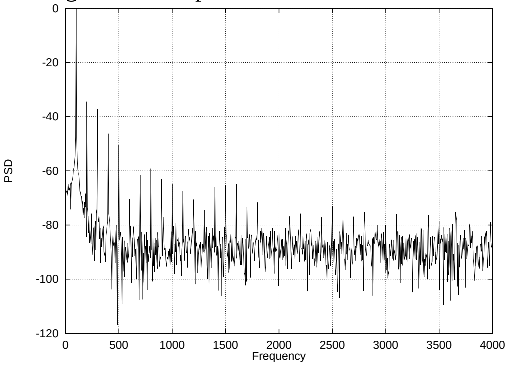

Figure 1. Typical interference spectrum of an incandescent lamp.

This interfering signal produced by incandescent lamps is an almost perfect sinusoid with a frequency of 100 Hz[1]. In addition to the 100 Hz sinusoid, only the first harmonics (up to 2 kHz) carry a significant amount of energy, and for frequencies higher than 800 Hz all components are more than 60 dB below the fundamental.
The same measurements were also performed using an optical filter and it was found that the interference amplitude is reduced by a factor of 1.5 (on average). This is about the same reduction achieved on the I_B current with the same optical filter. A comparison between the interference amplitude (peak-to-peak) and the background current (I_B) produced by the same light source shows that I_B is about 8.7 times higher than the interference amplitude.

A2.3. Fluorescent lamps

For the characterisation of the interference produced by fluorescent lamps, seven different types of fluorescent lamps equipped with conventional ballasts were tested. This group, picked from the large number of lamps available on the market, includes lamps of different electrical power, optical spectra (colour), different shapes and equipped with integrated ballasts (compact lamps) and external ballast.

[1] It should be noted that the mains power supply frequency is 50 Hz.

Despite the large number of different fluorescent lamps available, the interference they produce do not exhibit significant differences. However, the uniformity of the incandescent lamps is not present. The time waveforms and spectra are quite similar for all the types of lamps. Those of a 36W tubular lamp are shown in figure 2.

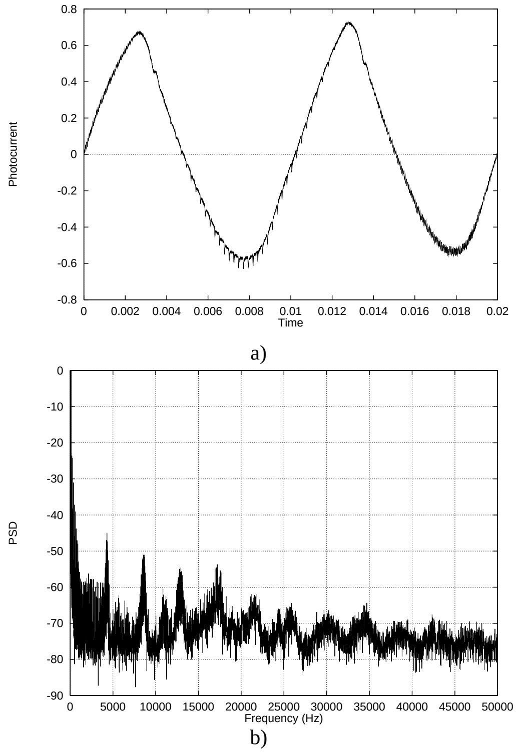

Figure 2. Fluorescent lamp interference: a) time waveform; b) spectrum.

The interference produced by a fluorescent lamp is a kind of distorted sinusoid. Compared to that of an incandescent lamp, its spectrum is much broader, extending up to 20 kHz or more. For frequencies higher than 5 kHz, the interference Power Spectral Density (PSD) is more than 50 dB bellow the 100 Hz component. The higher frequency components result from the "spikes" that can be observed in figure 2a and are very different from lamp to lamp. Another important characteristic of the fluorescent light interference is the existence of a component at 50Hz and at even harmonics of that frequency (50Hz, 150Hz, 250Hz, ...). This is in contrast with the incandescent light interference whose components are all harmonics of the 100 Hz fundamental. For the lower portion of the spectrum, there are also an envelope for the even harmonics and another for the odd harmonics of 50Hz.

For fluorescent lamps the interfering signal amplitude was found to be from 2 to 6 times lower than I_B when no optical filter is used. When the long-pass optical filter was used, surprising results were observed: the reduction achieved was found to vary from 11 to 20 times for I_B and from 4.7 to 8.9 for the interference amplitude. These results show that the steady irradiance and the time varying irradiance produced by fluorescent lamps have different optical spectra: the long-pass optical filter is more efficient in reducing I_B than for the interference. With the optical filter, I_B approaches the time average value of the interference.

The above results have been obtained after thermal stabilisation of both the lamp and the ballast. Measurements on the I_B current were performed during the warm-up period and the results show that from the turn-on instant until the end of thermal stabilisation, I_B increases about 25%. Thermal stabilisation occurs after about 5 minutes.
In addition to the effect described above, fluorescent lamps produce very strong transient interference signals when turned-on, but those are very difficult to characterise because they last for a few seconds, are very dependent from the lamp temperature and type of ballast and starter used. Moreover, its effect on the performance of wireless optical transmission systems may be neglected since transients last for only a few seconds.

A2.4. Fluorescent lamps geared by electronic ballasts

In the past few years, some lamp manufacturers introduced a new type of ballasts known as electronic ballasts. These devices adopt the same concept used in switching power supplies leading to a higher efficiency of the lamp-ballast assembly. This way less electrical power is required to produce the same levels of luminance, among other advantages. The switching frequency used to drive the lamps is not the same for all manufacturers but in the lamps we tested, we found that frequency to be in the 20-40 kHz range.

We measured the interference produced by several fluorescent lamps equipped with five different electronic ballasts and some unexpected results were obtained: the interference spectrum exhibits components at the switching frequency and at harmonics of that frequency, but also at low frequencies like conventional fluorescent lamps. One example of the interfering signal and spectrum produced by these kind of illuminating solutions is shown in figure 3.

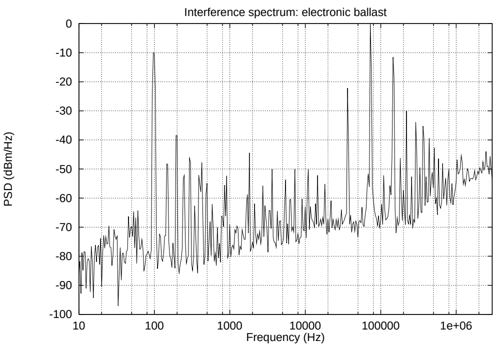

Figure 3. Spectrum of the interference produced by a fluorescent lamp geared by an electronic ballast.

Clearly, the spectrum shown in figure 3 have two distinct regions: the low frequency region where the interference is similar to that of a conventional fluorescent lamp and the high frequency region whose responsibility is the switching circuit of the electronic ballast. Other lamps have been also tested leading to similar results, except for the switching frequency and that for some lamps the high frequency interference component is stronger that the low frequency component.
Other measurements were performed, revealing that the amplitude of the interference produced by the same lamp when geared by an electronic ballast is lower than when it is geared by a conventional ballast (3 to 4 times lower). The I_B current resulting from the two configurations is similar.
There are also some drift on these parameters during the warm-up period as for conventional lamps: I_B increases from 15 to 30% and the interference amplitude decreases to less that 50% of its initial value.

B. Interference model

The interfering signals described in section A result in an optical power penalty in the infrared wireless transmission systems [11]. In order to estimate that penalty, a model of the interference is required. To estimate the systems performance, both analytical or simulation approaches may be adopted, and the interference model should be included in the channel model.

The background optical power that impinges on the receiver photodiode can be described by:

$$P_{opt}(t) = P_B + P_{interf}(t) \tag{1}$$

where P_B is the steady background optical power and $P_{interf}(t)$ is the time varying component. At the receiver photodiode, the collected optical power is converted into a current. As the result of the conversion process, the effects of this background irradiance manifest in two distinct forms: as shot noise with power proportional to the average photodiode current and as interference following the variations on the optical power. The photodiode output current can then be described by:

$$i_d(t) = I_B + i_{interf}(t) + i_{noise}(t) \tag{2}$$

If the bandwidth limitations of the photodiode are neglected (this approximation is valid within the frequency range of the interference), each of the components described in (2) can be related to the collected optical power (1) by simple expressions [9]:

$$I_B = \mathcal{R} \cdot P_B \tag{3a}$$

$$i_{interf}(t) = \mathcal{R} \cdot P_{interf}(t) \tag{3b}$$

$$\left\langle i^2{}_{noise} \right\rangle = 2 \cdot q \cdot I'_B(t) \cdot B \tag{3c}$$

with $I'_B(t) = I_B + i_{interf}(t)$ and where $\mathcal{R}$ is the photodiode responsivity, q is the electronic charge and B is the bandwidth. It must be noted that $I'_B(t)$ was used in (3c) instead of I_B since the "average" photodiode current may also be considered to vary in time. Since the interference amplitude and I_B are of the same order of magnitude, the shot noise may not be considered as an stationary random process.

The interference produced by the artificial light sources described above is a deterministic signal. For incandescent lamps and fluorescent lamps geared by conventional ballasts, the interfering signal is periodic with a period of 10 ms and 20 ms, respectively. For fluorescent lamps geared by electronic ballasts, the interfering signal is the sum of two distinct components: one similar to that produced by conventional fluorescent sources and another, also deterministic and periodic, generated by the high frequency switching circuits.

B.1. Incandescent lamps

The amplitude and phase of the 100Hz component and its harmonics were measured for six lamps and the average values (and 95% confidence intervals) were calculated. The results are shown in figure 4. These values are normalised to the magnitude of the 100Hz component.

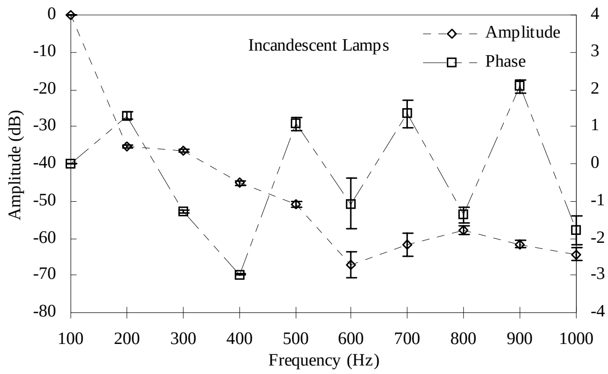

Figure 4. Average magnitude of the 100 Hz component and its harmonics.

The interfering signal can be described by a Fourier series as:

$$i_{incand}(t) = \frac{I_B}{F_1 \cdot A_1} \cdot \sum_{i=1}^{\infty} a_i \cdot \cos(2 \cdot \pi \cdot 100 \cdot i \cdot t + \phi_i) \qquad (4)$$

where a_i and ϕ_i are the relative amplitude and phase of each harmonic of 100 Hz, F_1 is the optical filter attenuation factor and A_1 is the constant that relates the interference amplitude with I_B. For this class, typical values for a_i and ϕ_i and can be easily identified, since most of the lamps produce very similar interference (see table 2). A_1 takes a value of about 8.7 for most of the lamps, while F_1 depends on the used optical filter (1.5 for our filter).

i	1	2	3	4	5	6	7	8	9	10
a_i	1.0	1.72 $\times 10^{-2}$	1.50 $\times 10^{-2}$	5.51 $\times 10^{-3}$	2.85 $\times 10^{-3}$	4.37 $\times 10^{-4}$	8.17 $\times 10^{-4}$	1.28 $\times 10^{-3}$	8.30 $\times 10^{-4}$	6.00 $\times 10^{-4}$
ϕ_i	0.00	1.30	-1.28	-2.98	1.07	-1.08	1.34	-1.37	2.09	-1.80

Table 2. Average parameter values for incandescent light interference.

B.2. Fluorescent lamps

The interference produced by different fluorescent lamps is very similar up to 2 kHz, but for higher frequencies each lamp produces a different interfering signal. For this reason, this paper will present a simple model only for frequencies up to 2 kHz. For higher frequencies, the proposed model does not apply.
The interfering signal can be described by:

$$i_{fluor}(t) = \frac{I_B}{F_2 \cdot A_2} \cdot \sum_{i=1}^{20} \left[b_i \cdot \cos(2 \cdot \pi \cdot (100 \cdot i - 50) \cdot t + \varphi_i) + c_i \cdot \cos(2 \cdot \pi \cdot 100 \cdot i \cdot t + \phi_i) \right] \qquad (5)$$

where b_i and φ_i the amplitude and phase of the even harmonics of 50 Hz, and c_i and ϕ_i are the amplitude and phase of the odd harmonics. F_2 is the optical filter attenuation factor and A_2 is the constant that relates the interference amplitude with I_B.

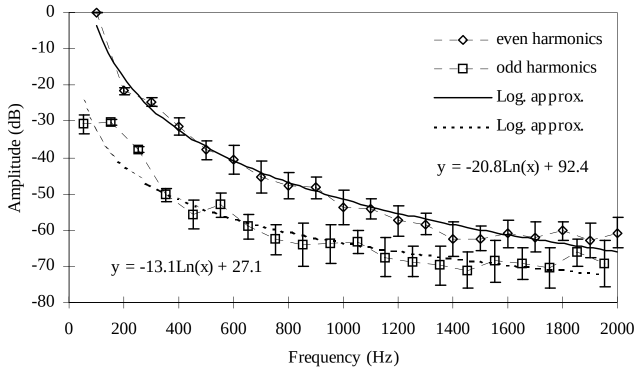

Figure 5. Average amplitude of each interference component.

For fluorescent lamps the parameters values may vary from lamp to lamp, a little more than for incandescent lamps. However, typical values representative of this class can be proposed. On average A_2 takes the value of 1.2 (with filter) and F_2 takes values between 4.7 to 8.9 for our optical filter. Figure 5 shows average values for the amplitude of even and odd harmonics of the 50 Hz fundamental taken from measurements on five lamps. Logarithmic approximations (using regression methods) to those values and 95% confidence intervals are also shown.
The amplitude parameters in (5) can then be estimated from:

$$b_i = 10^{\left(-13.1 \cdot \ln(100 \cdot i - 50) + 27.1 \middle/ 20\right)} \quad ,1 \le i \le 20 \qquad (6a)$$

$$c_i = 10^{\left(-20.8 \cdot \ln(100 \cdot i) + 92.4 \middle/ 20\right)} \quad ,1 \le i \le 20 \qquad (6b)$$

The phase values φ_i and ϕ_i are also very consistent up to 2 kHz. Typical values are presented in table 3.

i	φ_i	ϕ_i	i	φ_i	ϕ_i	i	φ_i	ϕ_i	i	φ_i	ϕ_i
1	4.65	0.00	**6**	5.98	5.70	**11**	1.26	6.00	**16**	5.49	3.69
2	2.86	0.08	**7**	2.38	2.07	**12**	1.29	6.17	**17**	4.45	1.86
3	5.43	6.00	**8**	4.35	3.44	**13**	1.28	5.69	**18**	3.24	1.38
4	3.90	5.31	**9**	5.87	5.01	**14**	0.63	5.37	**19**	2.07	5.91
5	2.00	2.27	**10**	0.70	6.01	**15**	6.06	4.00	**20**	0.87	4.88

Table 3. Typical values for the phase parameters.

B.3. Fluorescent lamps geared by electronic ballasts

For fluorescent lamps geared by electronic high-frequency ballasts, two components have to be modelled. Using an approach similar to that described above for conventional fluorescent lamps the interfering signal can be described by:

$$i_{elect}(t) = i_{low}(t) + i_{high}(t) \qquad (7)$$

where

$$i_{low}(t) = \frac{I_B}{F_3 \cdot A_3} \cdot \sum_{i=1}^{20} \left[b_i \cdot \cos(2 \cdot \pi \cdot (100 \cdot i - 50) \cdot t + \varphi_i) + c_i \cdot \cos(2 \cdot \pi \cdot 100 \cdot i \cdot t + \phi_i) \right] \qquad (8)$$

describes the low frequency component, and

$$i_{high}(t) = \frac{I_B}{F_3 \cdot A_4} \cdot \sum_{j=1}^{n3} d_j \cdot \cos(2 \cdot \pi \cdot f_{high} \cdot j \cdot t + \theta_j) \qquad (9)$$

describes the interference produced by the switching circuit of the electronic ballast.

For the low frequency component, the typical parameter values previously estimated for conventional fluorescent lamps may also be used in (8). For the interfering signal corresponding to the spectrum in figure 3, F_3 is about 3, $A_3 \approx 5.9$ and $A_4 \approx 2.1$. For the high frequency component, the parameters values f_{high}, d_j and θ_j are highly dependent on the type of electronic ballast. The switching frequency used by one manufacturer can be very different from that used by another one. Also the PSD produced by different ballasts may be very different. Again referring to figure 3 as an example, the parameter values in table 4 represent a typical case.

i	d_j (dB)	θ_j (rad)	**i**	d_j (dB)	θ_j (rad)
1	-22.2	5.09	**12**	-39.3	3.55
2	0.00	0.00	**14**	-42.7	4.15
4	-11.5	2.37	**16**	-46.4	1.64
6	-30.0	5.86	**18**	-48.1	4.51
8	-33.9	2.04	**20**	-53.1	3.55
10	-35.3	2.75	**22**	-54.9	1.78

Table 4. Typical values for the high frequency component.

C. Conclusions

This paper presented a characterisation of the noise and interference that natural and artificial light sources induce in wireless indoor optical communication systems. For the artificial light sources, three distinct classes of interfering devices showing similar characteristics have been identified:

Class 1: Incandescent lamps that produce narrow band interfering signals but that are very strong and very difficult to reduce by optical filtering since their optical spectra is very broad and extents to the infrared region. However, since the interference they produce is narrow band, electrical high-pass filter may be used to reduce its effects in transmission systems.

Class 2: Fluorescent lamps driven by conventional ballasts that also produce very strong interference with spectra extending up to several kHz. Optical filters provide much better results but higher reduction factors are achieved for the steady background current (I_B) than for the interference amplitude.

Class 3: Fluorescent lamps geared by electronic ballasts that produce lower amplitude interference but whose spectra is very broad, extending to more that 1MHz.

In order to evaluate the effects of the noise and interference induced by ambient light, a simple model to describe it was proposed and some examples of the parameters values were supplied.

It was found that interference produced by fluorescent lamps geared by electronic ballast is wider band and therefore it is expected to be the more important source of degradation in optical wireless communication systems.

The presented results suggest that a performance re-evaluation of the modulation and encoding schemes being used for optical wireless systems is required.

D. Acknowledgements

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