Reducing the Effects of Artificial Light Interference in Wireless Infrared Transmission Systems

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ABSTRACT

The performance of wireless infrared transmission systems for indoor use is severely impaired by the noise and interference induced by natural and artificial ambient light.
In order to combat the effects of ambient light on the system performance, both optical filtering and electrical filtering is usually adopted. However, even when resorting to these techniques, the optical power penalty imposed by the interference may be very large. In particular, the interference produced by fluorescent lamps driven by electronic ballasts imposes very large optical power penalties on systems operating at data rates up to a few tens of Mbps.
In this paper, a different technique to overcome the penalty induced by artificial light interference is analysed. This technique explores the different optical spectra of the transmitted signal and the artificial light and the characteristics of optical filtering to cancel the interfering signal. Some aspects of its implementation are also discussed.
The results obtained with this approach are shown to be much better than those obtained through electrical high-pass filtering.(*)

1. Introduction

Optical free space transmission systems are being proposed and used in a variety of wireless communication systems, from simple remote control systems for home appliances, to wireless local area networks [2,3,6,7].

The performance of wireless infrared links is impaired by several aspects [2-6]. From those, multipath dispersion is an important factor of degradation for data rates above 10 Mbps [3,15]. The other major impairment for indoor systems results from ambient light, and affects transmission systems operating at all data rates [2,10,13,14].

The average optical power that impinges the photodetector, due to natural and artificial ambient light, induces very high levels of shot noise that limits the performance of the transmission systems [10]. In addition, artificial light sources produce a time varying irradiance, resulting in an

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optical signal that interferes with the transmitted signal [11,13,14]. This interfering signal is periodic and deterministic [11].

The effects of ambient light have been combated by resorting to both optical filtering [2,12] and electrical filtering [13,14]. The use of optical filters reduces the amount of undesirable optical power that reaches the photodetector. The optical filter can be of the long-pass or band-pass type (interference filters). Interference optical filters are more efficient but they are very expensive which makes it difficult to use them in practical systems. Optical filters are efficient on the reduction of both the shot noise power and the interference produced by artificial lighting.

Since the power spectrum of the interference produced by artificial light sources is concentrated at low frequencies [11], electrical high-pass filters can be used to reduce the power penalty on transmission systems. The choice of the filter cut-of frequency is a compromise between the reduction on the interference that can be achieved and the amount of intersymbol interference (ISI) that is introduced. The effectiveness of electrical high-pass filters depends on the data rate and on the type of interference that is present.

The optical power penalty induced by the artificial light interference also depends on the type of modulation being used. In [13,14] it is shown that, for OOK-NRZ systems, the interference produced by incandescent lamps and fluorescent lamps driven by conventional ballasts can be effectively mitigated by combining optical filtering with electrical high-pass filtering. For L-PPM systems, the penalty induced by these two types of interference is considerably small if a Maximum-A-Posteriori (MAP) detector is used. However, the interference produced by fluorescent lamps geared by solid state ballasts induce very large power penalties even when electrical high-pass filtering is used, both on OOK-NRZ and L-PPM systems.

In this paper, a different technique to combat the effects of the artificial light interference is analysed. A similar solution was briefly suggested by Barry [1], but no analysis was provided to support the benefits of the technique. This technique explores the potentialities of optical filtering and the fact that the transmitted signal and the artificial light interference have different optical spectra, to cancel the interference.

The basic concept of the cancelling technique is presented in section 2. In section 3, some aspects of the implementation of this technique are discussed. Some results are presented in section 4. Section 5 presents the major conclusions.

2. Interference cancellation

In figure 1, the typical optical spectra of the optical sources involved in indoor wireless infrared transmission systems are shown [2,12]. The responsivity curve of a typical silicon PIN photodiode and the wavelength response of two optical filters are also shown.

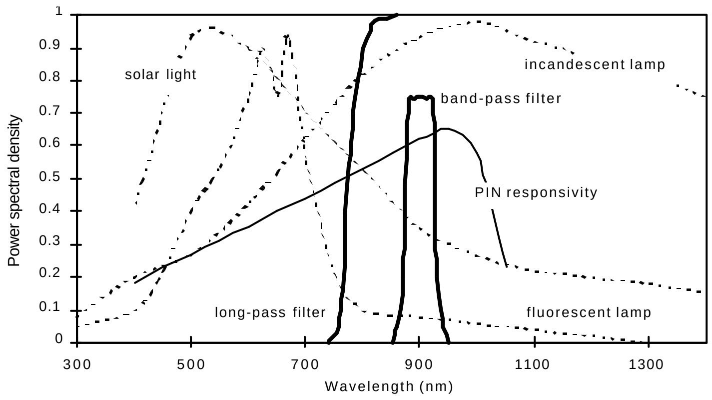

Figure 1. Typical optical spectra of optical sources.

Since the optical spectra of solar and artificial ambient light and the spectrum of the transmitted signal overlap in some extent, shot noise and interference are induced. The shot noise power is proportional to the optical power impinging on the photodetector and is one of the major aspects that limits the system performance. Additionally, artificial ambient light produces interference due to the time variations on its intensity. The characteristics of the interference (intensity and bandwidth) depends on the type of artificial light that produces it [11]. This interference induces a power penalty that in some cases may be very large. In particular, the penalty induced by the interference produced by fluorescent lamps driven by electronic ballasts is very large for systems operating up to 10 Mbps [13].

The use of optical filters, as those depicted in figure 1, reduces the amount of ambient light that reaches the photodetector, thus reducing the undesirable effects. The net gain obtained by the use of an optical filter depends on its efficiency in attenuating the ambient light while keeping intact the transmitted signal. Clearly, interference (band-pass) optical filters are more efficient in that operation, provided that the transmitted signal is not to attenuated as well. The efficiency of the optical filter does also depend on the type of ambient light that is present. In [11], it is shown that the attenuation provided by a long-pass optical filter is different for each type of ambient light source. Moreover, for fluorescent lamps, the attenuation achieved on the average optical power is different from the attenuation achieved on the interference amplitude.

The use of a differential receiver to cancel the interference was suggested by Barry [1]. That technique explores the optical filtering capabilities to cancel the interference produced by artificial light sources. In this paper, an analysis of a slightly different approach to reduce the effects of artificial light interference is performed. Consider the optical receiver depicted in figure 2.

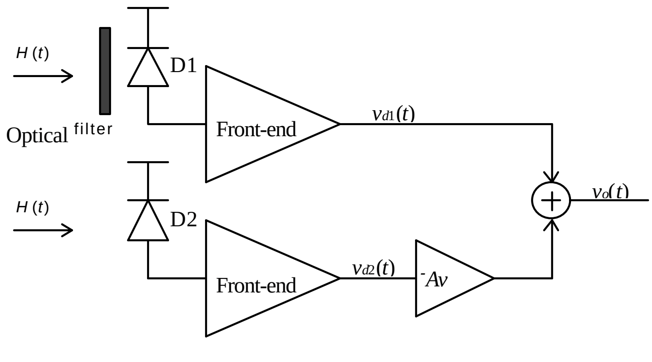

Figure 2. Optical receiver using optical filtering.

The concept of the interference cancellation is based on the fact that the transmitted signal and the interference have a different optical spectra. In figure 2, the upper front-end receives the transmitted signal and some amount of artificial light interference, as in a conventional receiver. The lower front-end receives the transmitted signal as well but the interference amplitude is much larger since no optical filter is used. The results is that the interference to signal ratio is much higher at the output of the lower front-end than at the upper front-end. If the output of the lower front-end is attenuated so that the amplitude of the interference received by the two stages is equal and the two outputs are subtracted, the interference is totally cancelled while the transmitted signal is only partially attenuated. This technique is now analysed.

The irradiance at the receiver site can be described as:

$$H(t) = H_s(t) + H_i(t) + H_a + H_n \tag{1}$$

where $H_s(t)$ is the irradiance produced by the transmitted signal, $H_i(t)$ is the time varying irradiance produced by the artificial light sources (with zero mean), H_a is the average irradiance produced by artificial lighting and H_n is the irradiance produced by solar light. Since the transmission coefficient of the optical filter for the irradiance produced by fluorescent lamps has different values for the average irradiance and for its time varying component [11], we have considered the two components separately.

The current in the photodetector D1 is then given by:

$$\begin{aligned} i_{d1}(t) &= \left[H_s(t)\cdot T_{s1}\cdot R + H_i(t)\cdot T_{i1}\cdot R' + H_a\cdot T_{a1}\cdot R'' + H_n\cdot T_{n1}\cdot R'''\right]\cdot A_r + i_{n1}(t) \\ &= i_{s1}(t) + i_{i1}(t) + I_{Ba1} + I_{Bn1} + i_{n1}(t) = i_{s1}(t) + i_{i1}(t) + I_{B1} + i_{n1}(t) \end{aligned} \tag{2}$$

where A_r is the photodetector active area, T_{s1}, T_{i1}, T_{a1} e T_{n1} are the transmission coefficients of the optical filter for the transmitted signal, time varying artificial light, average artificial light and solar light, respectively, and R, R', R'' and R''' represent the photodetector responsivity also for each irradiance component. Since the transmitted signal and each type of ambient light have different optical spectra, the transmission coefficient of the optical filter and the photodetector responsivity also have different values for each type of irradiance. In (2), $i_{s1}(t)$ is due to the transmitted signal, $i_{i1}(t)$ is the interfering signal, I_{B1} is the total d.c. current due to ambient light and $i_{n1}(t)$ is the shot noise due to the average d.c. photocurrent, with double side power spectral density N_1 given by:

$$N_1 = q\cdot\left(\langle i_{s1}(t)\rangle + I_{Ba1} + I_{Bn1}\right) = q\cdot\left(I_{Bs1} + I_{Ba1} + I_{Bn1}\right) \approx q\cdot I_{B1} \tag{3}$$

since $\langle i_{s1}(t)\rangle$ is usually very small.

Consider now the lower stage shown in figure 2 where the receiver is similar to the upper one but without the optical filter. In this case, the photodetector current is given by:

$$\begin{aligned} i_{d2}(t) &= \left[H_s(t)\cdot R + H_i(t)\cdot R' + H_a\cdot R'' + H_n\cdot R'''\right]\cdot A_r + i_{n2}(t) \\ &= i_{s2}(t) + i_{i2}(t) + I_{Ba2} + I_{Bn2} + i_{n2}(t) = i_{s2}(t) + i_{i2}(t) + I_{B2} + i_{n2}(t) \end{aligned} \tag{4}$$

with

$$N_2 \approx q \cdot I_{B2} \tag{5}$$

At the output of each front-end in figure 2, $v_{d1}(t)$ and $v_{d2}(t)$ is a scaled replica of $i_{d1}(t)$ and $i_{d2}(t)$, respectively, if the receiver noise is neglected, as it is often the case, and assuming a linear front-end.

We note that the interfering signal is deterministic. If now we multiply $v_{d2}(t)$ by the transmission coefficient of the filter for the interference signal, $Av=T_{i1}$, and subtract the result from $v_{d1}(t)$, we have, after dropping the d.c. components:

$$v_o(t) = v_{d1}(t) - v_{d2}(t) \cdot T_{i1} = H_s(t) \cdot R \cdot (T_{s1} - T_{i1}) \cdot A_r + v_{n1}(t) - v_{n2}(t) \cdot T_{i1} = v_{st}(t) + v_{nt}(t) \tag{6}$$

and the interference is cancelled, provided that $T_{i1} \neq T_{s1}$. As described in [11], for a long-pass optical filter $T_{s1} \approx 1$ and T_{i1} may vary between 0.01 (for fluorescent light) and 0.67 (for incandescent light).

Equation (6) shows that the artificial light interference can be cancelled. However there is still a price to pay: the amplitude of $v_{st}(t)$, A_{st}, is decreased and the noise power, N_t, is increased:

$$A_{st} = A_{s1} \cdot \frac{T_{s1} - T_{i1}}{T_{s1}} \tag{7}$$

$$N_t = N_1 + T_{i1}^{\ 2} \cdot N_2 \tag{8}$$

We define the signal to noise ratio *SNR* as:

$$SNR = \frac{A_s \cdot \sqrt{T_b}}{\sqrt{2 \cdot N_0}} \tag{9}$$

such that a variation of 1 dB in the SNR corresponds to the same variation on the optical power requirements.

At the output of receiver 1, the *SNR* is:

$$SNR_1 = \frac{A_{s1} \cdot \sqrt{T_b}}{\sqrt{2 \cdot N_1}} \tag{10}$$

and after the cancellation operation, the *SNR* is:

$$SNR_t = \frac{A_{s1} \cdot \frac{T_{s1} - T_{i1}}{T_{s1}} \cdot \sqrt{T_b}}{\sqrt{2 \cdot \left(N_1 + T_{i1}^{\ 2} \cdot N_2\right)}} \tag{8}$$

We define the penalty due to the cancellation operation, over a system operating without interference (with optical filtering), as:

$$Penalty = 10 \cdot Log\left(\frac{SNR_1}{SNR_t}\right) = 10 \cdot Log\left(\frac{\sqrt{1 + T_{i1}^{\ 2} \cdot \frac{N2}{N1}}}{1 - \frac{T_{i1}}{T_{s1}}}\right) \tag{9}$$

In practical systems the optical filter is chosen so that none or small attenuation on the transmitted signal is inserted by the optical filter ($T_{s1}\approx 1$). Equation (9) shows that the more efficient the optical filter in the attenuation of the artificial light interference, i.e., the lower the value of T_{i1}, the smaller is the penalty due to the cancellation operation.

We note that this technique is applicable to any type of artificial light interference, incandescent light and fluorescent light with and without electronic ballasts, or any combination of them. In the last case, T_{i1} is the overall transmission coefficient of the optical filter for the total irradiance produced by the artificial light sources.

3. Implementation aspects

The cancellation technique described above, requires the estimation of the transmission coefficient of the optical filter for the artificial light, T_{i1}, so that the gain of the amplifier, Av, can be adjusted.

From equations (2) and (4) it is clear that $T_{i1}=i_{i1}(t)/i_{i2}(t)$. Since all classes of interference have a strong spectral component at double of the frequency of the mains power supply (50 or 60 Hz) [11], a good estimate of T_{i1} can be obtained by calculating the ratio $v_{d1}'(t)/v_{d2}'(t)$, where $v_{d1}'(t)$ and $v_{d2}'(t)$ are low-pass filtered versions of $v_{d1}(t)$ and $v_{d2}(t)$, respectively (figure 3a). The cut-off frequency of the low-pass filters should be set to a few hundred Hz so that the interference-to-noise ratio be as high as possible.

Alternatively, a control sub-system with feedback can be used to minimise the amplitude of a low-pass filtered version of the total received signal through the dynamic adjustment of the amplifier gain Av (figure 3b).

Both approaches should be able to provide good estimates of T_{i1}, even for low values of the interference-to-noise ratio or interference-to-signal ratio.

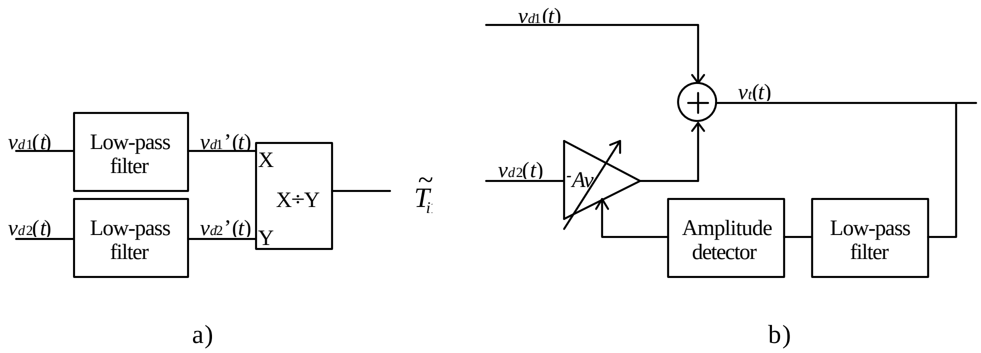

Figure 3. Estimation of *Av*.

It is known that the ambient light conditions in a particular environment are not constant in time, and very different conditions may be found along the period of a single day. A very common situation is the one where the ambient light is only natural during the day and artificial at night. In this case, when the ambient light is only natural there is no interference. The implementation of the technique described in this paper should cope with this situation. A simple solution to this problem is to detect the presence of interference, again through the estimation of the amplitude of a low-pass filtered version of the received signal ($v_{d1}(t)$ or $v_{d2}(t)$). If that amplitude is lower than a pre-defined level, then the value of Av should be set to zero so that no unnecessary noise is added to the signal.

In section 2 we have considered two photodetectors, D1 and D2 in figure 2, with similar characteristics such as active area and responsivity. We note that different photodetectors can be used for D1 and D2. In the case of different photodetectors, the expression for the power penalty presented in section 2 (equation 9), should be changed to take into account the different characteristics of the two photodetectors.

In order to improve the system performance, the shot noise introduced by the second photodetector can also be reduced by using a second optical filter in D2. This second filter should not transmit the signal while transmitting the interference.

4. Results

In [13,14] the power penalty induced by artificial light interference was estimated with and without electrical high-pass filtering, and the results show that for the interference produced by fluorescent lamps driven by electronic ballasts the penalty can be very large.

In this section we compare the penalty induced by artificial lighting when high-pass filtering is used with the penalty obtained by using the cancellation technique described in section 2.

We consider here a case where I_{Bn2}=200 μA, I_{Ba2}=2 μA, T_{s1}=1, T_{i1}=1/4.7, T_{a1}=20 and T_{n1}=3.9, as in [13] and where the transmission coefficients of the optical filter are those reported in [11]. In this case we have:

$I_{Bn1}=I_{Bn2}/T_{n1}=780\ \mu A$
$I_{Ba1}=I_{Ba2}/T_{a1}=40\ \mu A$
$N_1=3.24\times10^{-23}\ A^2/Hz$
$N_2=1.31\times10^{-22}\ A^2/Hz$

In Table 1 the penalties induced by artificial light interference produced by fluorescent lamps driven by electronic ballasts on a system operating a 1 Mbps, and using the same optical filter as the one considered in this paper, are presented [13]. In Table 1, the penalties obtained through the use of the cancellation technique are comprared to the penalties obtained when electrical high-pass filtering is used to combat the interference.

	OOK-NRZ	16-PPM, MAP	16-PPM,TH
Without high-pass filtering	17.3 dB	13.0 dB	-
With high-pass filtering	17.1 dB	8.9 dB	10.0 dB
Using cancellation	1.8 dB	1.8 dB	1.8 dB

Table 1. Power penalty induced by fluorescent lamps driven by electronic ballasts.

These results show that the cancellation technique is much more efficient than simple high-pass filtering in combating the interference. For systems operating at lower data rates, the advantage of this approach is even higher, since the power penalties with high-pass filtering are higher.

Equation (9), also shows that the penalty due to the cancellation technique depends on the shot noise levels with and without optical filtering. We have performed the calculation of the penalty for two other ambient light conditions corresponding to I_{Bn2}=20 μA and I_{Bn2}=2000 μA, and we found the penalty to be:

I_{Bn2}=20 μA Penalty=1.98 dB
I_{Bn2}=2000 μA Penalty=1.75 dB

showing that the penalty is almost insensitive to the natural ambient light levels.

In the first penalty calculation we have considered a high value for T_{i1} (T_{i1}=1/4.7). We have repeated the penalty calculations for a lower value of T_{i1}=1/8 [11], and we found the penalty to be much lower:
T_{i1}=1/8 Penalty=0.85 dB

as anticipated in section 2.

5. Conclusions

Ambient artificial light produces interference that induces a power penalty in indoor optical wireless transmission systems. For data rates higher than 1 Mbps, the interference produced by incandescent lamps and fluorescent lamps driven by conventional ballasts can be effectively mitigated by resorting to a combination of optical filtering and electrical high-pass filtering. However, the interference produced by fluorescent lamps driven by electronic ballasts induces very large power penalties, even when electrical high-pass filtering is used.

A technique to reduce the effects of artificial light interference through the cancellation of the interfering signal was described. This technique is applicable to all types of artificial light interference and is effective for systems operating at a wide range of data rates.

The results show that this technique is much more effective than electrical high-pass filtering in mitigating the effects of artificial light interference.

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