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# Wireless Optical PPM Telemetry and the Influence of Lighting Flicker

Rob Otte, Leo P. de Jong, and Arthur H. M. van Roermund, *Senior Member, IEEE*

**Abstract**—Digital pulse-position modulation (PPM) is attractive to apply in wireless optical-telemetry systems because of its power efficiency. Usually, the bit-error rate is assumed to depend solely on the noise level. The detrimental influence of optical interference is overlooked. In this paper, interference measurements are reported, models that describe interference are presented, and it is shown that the influence of interference can be significant. Further, new rules for system design in the presence of interference are reported. It appears that, compared with the influence of noise, the flicker of incandescent lamps is usually negligible, but the flicker of fluorescent lamps is not negligible.

**Index Terms**—Intensity modulation, interference, optical communication, optical modulation/demodulation, optical receivers, optical signal detection, pulse position modulation, telemetry.

## I. INTRODUCTION

**I**N MANY situations, telemetry which uses radio systems is undesirable because of problems with respect to electromagnetic compatibility (EMC), governmental regulations on frequency allocation, or information safety. For indoor applications, wireless optical infrared telemetry can be an attractive alternative, since optical radiation is confined to the user's premises, so that the above-mentioned problems hardly occur. Therefore, infrared transmission became popular as soon as the appropriate components, such as infrared LED's and Si detectors, became available in the late 1970's [1].

In mobile telemetry systems, a limited transmitter complexity and a small power consumption are of utmost importance. In such cases, digital pulse position modulation (PPM), based on intensity modulation and direct detection, is a very suitable modulation scheme, because it combines the advantages of digital transmission (easy multiplexing of sensor signals, the possibility for data compression and error correction) and small duty-cycle pulse transmission (low-power transmitter) [2]–[4].

First, the PPM scheme and the receiver are described in Section II. The system design is based on the fact that the main source of noise is the detector shot noise caused by ambient radiation.

Second, the detrimental influence of interference caused by ambient radiation is investigated in Section III, so that the limitations of the white noise approach can be taken into

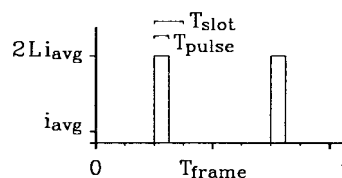


Fig. 1. The PPM modulation scheme.

account, and new design rules to overcome the influence of interference are derived.

Finally, Section IV summarizes the conclusions.

## II. MODULATION, SYNCHRONIZATION, AND DEMODULATION

In a PPM modulator, an input word consisting of several bits is converted into the position of a pulse within a frame. This is shown in Fig. 1. The frame, with duration  $T_{frame}$ , is divided into  $L$  slots with duration  $T_{slot}$  and only one of these slots contains an optical pulse. Since  $L$  possible pulse positions are used to code  $\log_2 L$  bits of information, the bit rate follows as  $R_b = \log_2 L / T_{frame}$ . Initially, we assume the pulses to be rectangular. The height of the pulses is normalized such that the average current through the receiver photodiode is  $i_{avg}$ . It is an important quantity, since it depends on the transmitted optical power. Therefore, it indirectly determines the average power consumption of the transmitter and thus the battery lifetime. Because the information is represented by the position of the pulses, the receiver has to operate synchronously, i.e., it requires a slot and frame synchronization system. To facilitate slot synchronization by means of a phase-locked loop (PLL), the pulse duration is chosen to be equal to half the slot duration [3], [5]. Therefore, the scheme is also called “half-pulse PPM.” This indicates the contrast with “full-pulse PPM,” in which the pulse duration equals the slot duration. Apart from the slot timing, the frame timing has also to be known before demodulation is possible. By utilizing the knowledge that every PPM frame contains exactly one pulse, frame synchronization can be achieved [4].

When comparing PPM to other transmission schemes such as on–off keying, the BER and the minimally required transmission bandwidth  $B$  have to be calculated.

The demodulator is assumed to be a maximum likelihood integrate-and-dump (I&D) demodulator, i.e., a demodulator that assumes the PPM pulse to originate from the pulse interval in which most optical energy was found [6]. For adequately designed receivers, the main source of noise is the photodetector shot-noise current caused by ambient radiation.

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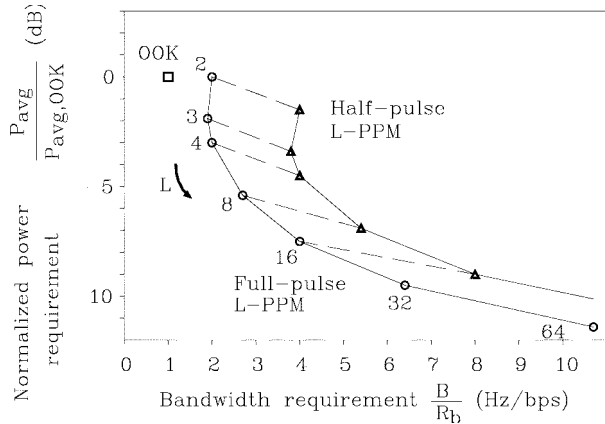


Fig. 2. Comparison of required transmitter power and required transmission bandwidth.

This white-noise process is described by its double-sided spectral density  $N_0 = qI_{amb} A^2/\text{Hz}$ , where  $q$  is the electron charge and  $I_{amb}$  is the photodiode quiescent current due to ambient radiation. For Gaussian noise, the bit error rate (BER) of our demodulator can be calculated as [2], [3]

$$\begin{aligned} \text{BER} &= \frac{L}{2} Q\left(\sqrt{L \log_2 L} \frac{i_{avg}}{\sqrt{N_0 R_b}}\right) \\ &\approx Q\left(\sqrt{L \log_2 L} \frac{i_{avg}}{\sqrt{N_0 R_b}}\right) \end{aligned} \quad (1)$$

in which  $Q(k) = (1/\sqrt{2\pi}) \int_k^\infty \exp(-(1/2)\lambda^2) d\lambda$  is the noise distribution function and  $i_{avg}$  is the average PPM photocurrent. In power budget calculations, the applied approximation is usually allowed, since  $Q(k)$  is a rather steep function.

Subsequently, the required transmission bandwidth has to be calculated. Since the transmitter spectrum extends to infinity, an estimation has to be made. In [3], it was shown that for our demodulator  $B = 1/T_{pulse}$  is a reasonable estimate.

In Fig. 2, the required transmitter power  $P_{avg}$ , which corresponds to a detector current of  $i_{avg}$ , and the required transmission bandwidth  $B$  of full-pulse PPM and half-pulse PPM are compared in relation to on-off keying. The figure illustrates that for low-power telemetry PPM is much more suitable than on-off keying, especially when the bit rate is low compared to the available channel bandwidth. Further, it appears that transmitter power can be saved at the expense of additional transmission bandwidth by increasing the number of slots per frame  $L$ , thereby allowing a compromise between power consumption and transmission bandwidth.

A prototype half-pulse PPM system, with  $L = 4$ , was realized with discrete components to verify the theory. The BER was measured at a bit rate of 5 kbps. The results are shown in Fig. 3 as a function of  $k$ , i.e., as a function of the argument of the function  $Q(\cdot)$ . The deterioration in sensitivity compared with (1) is about 0.4 dB (optical power level), mainly due to slot clock jitter. The maximum bit rate follows from the channel bandwidth. In our indoor telemetry application, this bandwidth is in the order of 10 MHz due to multipath dispersion. This allows maximum data rates of about 2.5 Mbps.

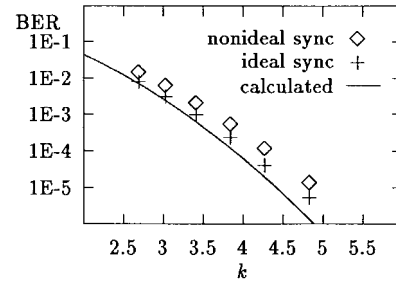


Fig. 3. Measured and calculated values of the BER versus  $k$ .

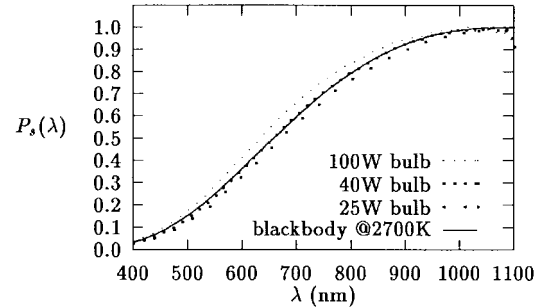


Fig. 4. Relative spectra of standard bulbs. For comparison, the spectrum of a blackbody at 2700 K is also shown.

### III. INTERFERENCE DUE TO AMBIENT RADIATION

In the previous section, it was assumed that the bit error rate is determined by the detector shot noise, caused by ambient radiation. However, lighting does not only cause noise, but it might also interfere with the PPM signal because of lamp flicker. In particular, systems that have been optimized with regard to noise, by choosing a large photodetector area, are sensitive to this optical interference. Therefore, the influence of interference is investigated separately in this section. First, the amount of infrared radiation in the range  $800 \text{ nm} < \lambda < 1000 \text{ nm}$  is determined for sunlight, incandescent light, and fluorescent light. Then, the modulation properties of the sources are investigated.

#### A. The Sun

For sunlight, the amount of infrared radiation is known [7]: the maximum solar spectral irradiance is in the range  $0.25 \text{ W/m}^2 \text{ nm} < E_{e,\lambda} < 1.0 \text{ W/m}^2 \text{ nm}$ , so that noise levels can readily be calculated if the area, the responsivity, and the optical bandwidth of the detector are known. Modulation effects are hardly of importance.

#### B. Incandescent Lighting

For incandescent light, the situation is more complicated since incandescent lamps suffer from flicker due to the mains frequency. The amount of infrared radiation of several standard 230 V incandescent lamps was measured by means of a double monochromator. The spectra are shown in Fig. 4. Within the wavelength range considered, the lamps behave like blackbodies at a temperature of 2700 K. For design purposes, the amount of infrared radiation relative to the

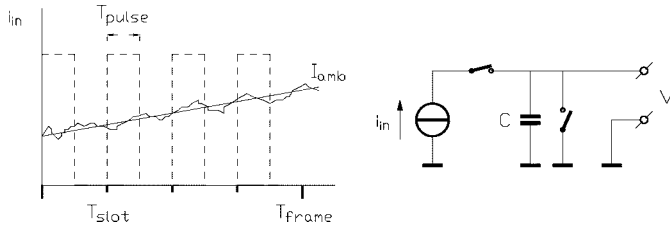


Fig. 5. Signals at the receiver input and the schematic of the I&D demodulator filter. The input signal  $i_{in}$  consists of three components: the PPM signal current, a parasitic current due to ambient radiation  $I_{amb}$ , and the shot noise component of this latter current. The switches in the I&D filter are controlled such that the filter is integrating during the dashed intervals.

amount of visible light is a suitable measure. Therefore, the optical spectrum was normalized to 1 lm. The result is called the “infrared-to-visible ratio,” or IRTV. For blackbodies at a temperature of 2700 K, the IRTV is in the range  $41 \mu\text{W}/\text{lm}\cdot\text{nm} < \text{IRTV} < 50 \mu\text{W}/\text{lm}\cdot\text{nm}$ , depending on the wavelength. The detector current due to ambient light follows from

$$I_{amb} = \int_0^\infty R(\lambda)F(\lambda)\text{IRTV} d\lambda \cdot \Phi_v. \quad (2)$$

In this expression,  $R$  is the detector responsivity,  $\Phi_v$  is the luminous flux incident on it, and  $F$  is the filter transmission. The lamp flicker was measured at a mains frequency of 50 Hz, in the wavelength span  $850 \text{ nm} < \lambda < 1050 \text{ nm}$ . Due to filament lag, the ripple on the intensity is almost sine shaped, with a frequency of  $f_i = 100 \text{ Hz}$  and an amplitude that approximately equals 10% of the average intensity [8]. Thus, the modulation index of the lamp is said to equal  $m_i = 10\%$ .

The influence of flicker and other intensity variations can be modeled after considering Fig. 5. In the model, we assume that the level of ambient radiation varies only slowly, compared with the PPM signal, so that its first-order derivative is satisfactory in describing its variations. Further, it is assumed that  $I_{amb}$  is modulated only weakly, so that the level of shot noise is approximately constant. For incandescent lamps, these approximations are valid in almost all practical situations. The maximum slope of  $I_{amb}$  follows from the interfering frequency and the modulation index of the lamp as

$$\left. \frac{dI_{amb}}{dt} \right|_{\max} = 2\pi m_i f_i I_{amb}. \quad (3)$$

Lamp flicker is negligible provided that the difference between the last and the first integration result,  $\Delta_i(V)$ , is smaller than the rms variations of the integration results due to noise,  $\sigma_n(V)$ . The transfer of the I&D filter, from the input current to the output voltage at the end of an integration interval, is defined by the impulse response and its Fourier transform, respectively, as

$$h(t) = \begin{cases} \frac{1}{C}, & \text{if } 0 \leq t \leq T_{\text{pulse}} \\ 0, & \text{elsewhere} \end{cases} \quad (4)$$

$$H(f) = \frac{V(f)}{i_{in}(f)} = \frac{T_{\text{pulse}}}{C} \text{sinc}(\pi f T_{\text{pulse}}) \exp(-j\pi f T_{\text{pulse}}) \quad (5)$$

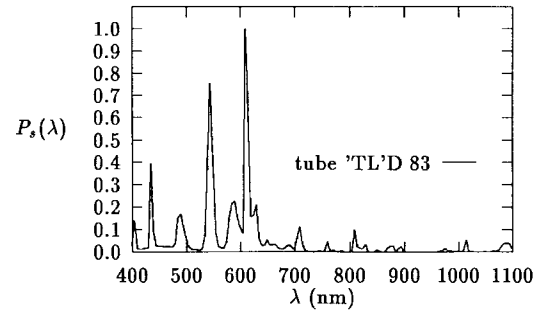


Fig. 6. Relative spectrum of fluorescent tube “TL”D 83.

with  $\text{sinc}(x) = (\sin(x)/x)$ . From the filter response,  $\Delta_i(V)$  and  $\sigma_n(V)$ , respectively, follow as

$$\Delta_i(V) = \frac{(L-1)T_{\text{frame}}}{L} \frac{T_{\text{pulse}}}{C} \left. \frac{dI_{amb}}{dt} \right|_{\max} (V) \quad (6)$$

$$\sigma_n(V) = \frac{1}{C} \sqrt{N_0 T_{\text{pulse}}}(V). \quad (7)$$

In these expressions  $C$  is the value of the capacitor in the I&D filter. In practice,  $(L-1)/L \approx 1$ , since only  $L \geq 4$  allows for low-power transmission, and  $T_{\text{pulse}} = (T_{\text{frame}}/2L)$ . Now  $\Delta_i(V) < \sigma_n(V)$  holds provided that

$$I_{amb} < \frac{qL}{2\pi^2 m_i^2 f_i^2 T_{\text{frame}}^3}. \quad (8)$$

This means that, in particular, systems that are optimized with regard to noise by means of a large detector area, or a large number of slots per frame, might suffer from lamp flicker. It also means that low-speed systems are more sensitive to lamp flicker than high-speed systems. In practice, (8) is only violated very close to the lamp, indicating that special measures, such as hum filtering, are not required, and that (1) remains valid.

### C. Fluorescent Lighting

Like incandescent lamps, fluorescent lamps also suffer from flicker. In lighting systems that employ a traditional inductive ballast circuit, the flicker frequency equals twice the mains frequency. Today, high-frequency ballast circuits are often used to obtain better lamp performance. In those cases, the flicker frequency is usually in the range of 40 kHz to 100 kHz. At the same time, the modulation index is large, i.e., in the range 50% to 100%, depending on the supply frequency [8].

To investigate when lamp flicker is detrimental, the amount of infrared radiation was measured for several lamps. Since the results are approximately the same, only one of the spectra, obtained from the commonly used Philips 36 W tube “TL”D 83, is given as a plot in Fig. 6. The spectral lines are partly caused by the emission lines of mercury, and partly by the emission lines of the phosphors inside the tube [9]. It appears that, at the same illuminance, fluorescent lamps produce much less infrared radiation than incandescent lamps. To investigate the amount of infrared radiation more accurately, the spectrum was normalized to 1 lm, resulting in the IRTV plot shown in Fig. 7. This figure is used to determine the detector current from (2).

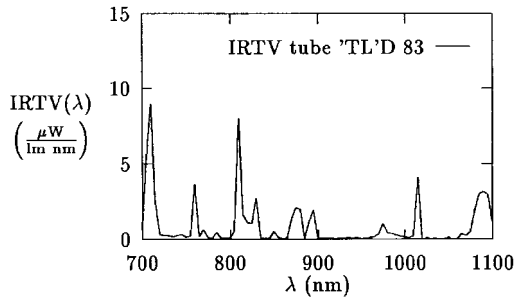


Fig. 7. IRTV of fluorescent tube "TL"D 83 (wavelength resolution 5 nm).

When operated at the mains frequency, lamp flicker can be modeled as before. When operated at a high-frequency ballast circuit this is not possible, since the interfering frequency is in the order of the frame rate, or even faster. In such cases, the influence of flicker should be investigated *per slot*. Again, the interfering signal can be approximated as a sine wave. The rms variations of the integration results due to flicker equal

$$\sigma_i(V) = |H(f_i)|i_i(V). \quad (9)$$

In this expression  $i_i = (1/2)\sqrt{2}m_i I_{amb}$  is the rms value of the interfering current and  $f_i$  is its frequency. Lamp flicker is negligible compared to noise provided that  $\sigma_i(V) < \sigma_n(V)$ . This requirement holds provided that

$$I_{amb} < \frac{2q}{T_{pulse} m_i^2 \text{sinc}^2(\pi f_i T_{pulse})}. \quad (10)$$

#### D. Design Example

In this example, we investigate the influence of fluorescent lamp flicker on the link quality of a 100 kbps half-pulse 4-PPM system. The flicker frequency of the lamp is  $f_i = 100$  kHz. Its modulation index is 50%. Since the bit rate is 100 kbps, the system has  $T_{frame} = 20 \mu s$  and  $T_{pulse} = 2.5 \mu s$ . The detector has an area of  $A_{det} = 200 \text{ mm}^2$ , a responsivity of  $R = 0.6 \text{ A/W}$ , and an optical bandwidth of  $B_{opt} = 100 \text{ nm}$  centered at 900 nm. The detector is illuminated at a level of  $E_v = 500 \text{ lm/m}^2$ . This illumination is typical of desktops in offices.

The detector current follows from (2) as  $I_{amb} = R \int_{850\text{nm}}^{950\text{nm}} \text{IRTV} d\lambda \Phi_v = 2.9 \mu A$ , and we find

$$\sigma_i(V) = \frac{2.32 \cdot 10^{-12}}{C} > \sigma_n(V) = \frac{1.08 \cdot 10^{-15}}{C}(V). \quad (11)$$

Clearly, the effect of lamp flicker exceeds the effect of noise by far, even when the receiver is not very close to the lamp. The reason is that, on the one hand, the noise level is low, since the level of infrared radiation is low, while, on the other hand, the effect of flicker is large, since the modulation index is large and the flicker frequency is close to the slot rate. Even when the lamp is operated at the mains frequency, lamp flicker is usually more detrimental than noise. Thus, (1) is not a suitable design rule. Instead, one has to be ensured that the integration result caused by the PPM pulse, which has a value of  $(T_{frame}/C)i_{avg}$ , exceeds the variation of the integration results due to lamp flicker as given by (6) or (9).

## IV. CONCLUSIONS

In this paper, measurements of the influence of optical interference on the link quality have been described and modeled. Design rules to overcome the effect of interference were derived. It appears that the flicker of incandescent lamps is often negligible when compared with the detrimental effect of shot noise. Flicker of fluorescent lamps cannot be neglected, particularly when the lamps are driven from high-frequency ballast circuits.

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