Dipartimento INFOCOM
Università degli Studi di
Roma "La Sapienza"

Departamento de Señales y
comunicaciones
ULPGC

Optical Communications

Telecommunication Engineering
School of Engineering
University of Rome La Sapienza
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Noise

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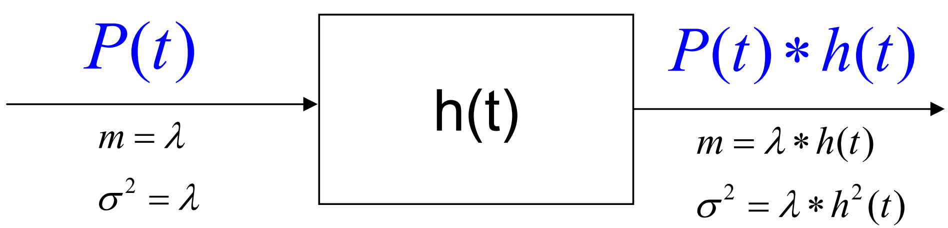
A typical noise in Optical receivers: SHOT NOISE

Shot noise is a filtered POISSON process

$$\text{Prob}(N = k) = \lambda^k \frac{e^{-\lambda}}{k!}$$



P(t) : arriving photons

h(t) : impulse response of the photodetector

*P(t)*h(t)* : generated electrons

High intensity shot noise: when the intensity of shot noise is high the statistics become that of a Gaussian random process

NOISE SOURCES

- Noise sources can be organized into several categories:

Environmental noise sources

- ❑ Sunlight irradiance produces shot noise in the photodiode that can be considered as **white gaussian noise** (it can be reduced by using tinted lenses that avoid visible and UV spectral components)

- ❑ Artificial lamps irradiance (incandescent, halogen and fluorescent) produce shot noise in the photodiode that can be considered as a **narrowband interference**

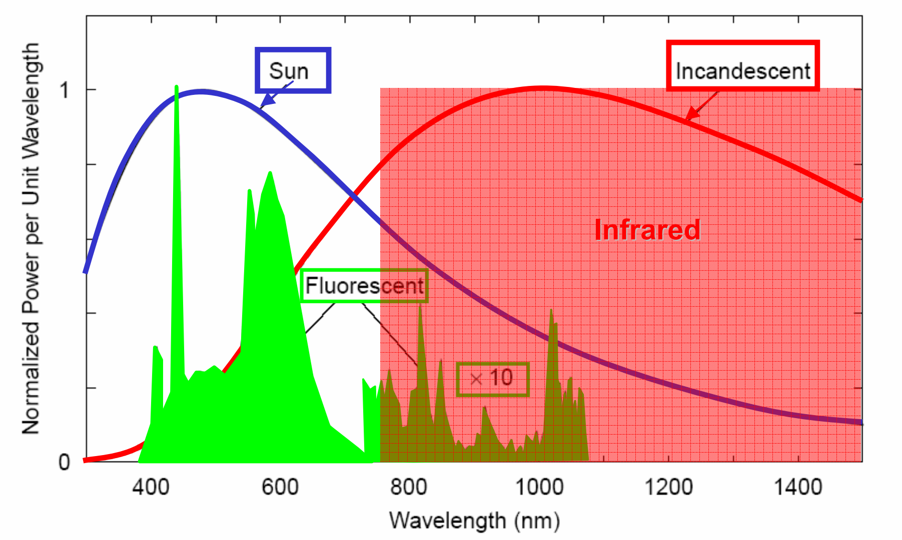
- ❑ Thermal noise in the receiver, modeled by the Boltzmann equation

- ❑ Dark leakage current (depending on technology considerations from the photodiode)

SOURCES OF ENVIRONMENTAL NOISE

Common environments contain intense ambient infrared radiation:

- Sunlight
- Skylight
- Incandescent and fluorescent lamps



Sunlight, skylight and incandescent lamps are essentially unmodulated sources that are eventually received at an average power that is much larger than the desired signal, even when optical filtering is employed.

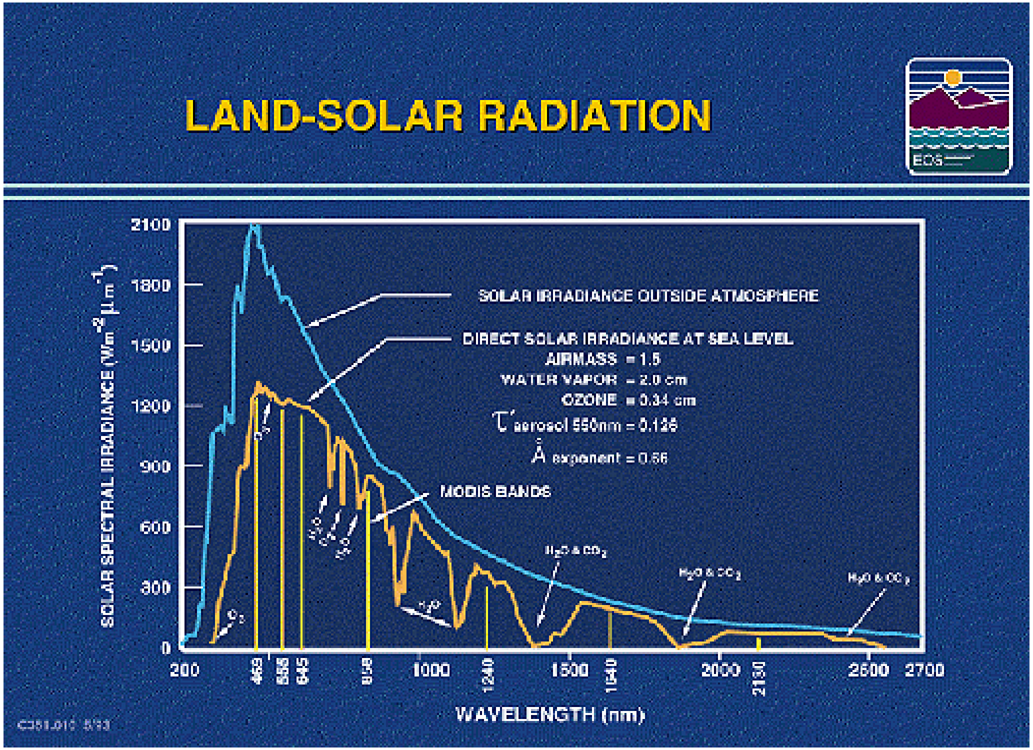
The resulting d.c. photocurrent causes shot noise, which is a dominant noise source in typical infrared receivers.

SOLAR RADIATION NOISE

Solar irradiation, also called insolation, arrives at Earth at wavelengths that are determined by the photospheric temperature of the sun (peaking near 5600 °C).

The main wavelength interval is between 200 and 3400 nm (0.2 and 3.4 µm), with the maximum power input close to 480 nm (0.48 µm), which is in the visible green region.

As solar rays arrive at Earth, the atmosphere absorbs or backscatters a fraction of them and let the remainder go through.



AMBIENT LIGHT NOISE

Ambient light noise is assumed to have a spectral irradiance p_n [W/(cm^2 x nm)] that is independent of wavelength within the filter bandwidth.

If the ambient light originates from a localized source, and supposing that a receiver of area A is hit by this irradiance, the received ambient optical average power P_n is:

$$P_n = p_n \Delta\lambda_n A$$

AMBIENT LIGHT NOISE CHARACTERIZATION

The background irradiance produced by natural and artificial light sources is usually characterized by the d.c. current it produces in the receiver photodiode since the resulting shot noise power is directly proportional to that current (**background current I_B**).

I_B for conventional-driven and electronic-driven ballast for fluorescent tubes are similar.

Lower cut-off frequency of 800 nm

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

Background current I_B for several illumination conditions

THERMAL NOISE CHARACTERIZATION

Thermal noise is introduced by the output resistance of the device *R*, that is after optical/electrical conversion. The Power Spectral Density of this noise (noise is a current here) is:

$$P_{thermal}(f) = \frac{2kT}{R}$$

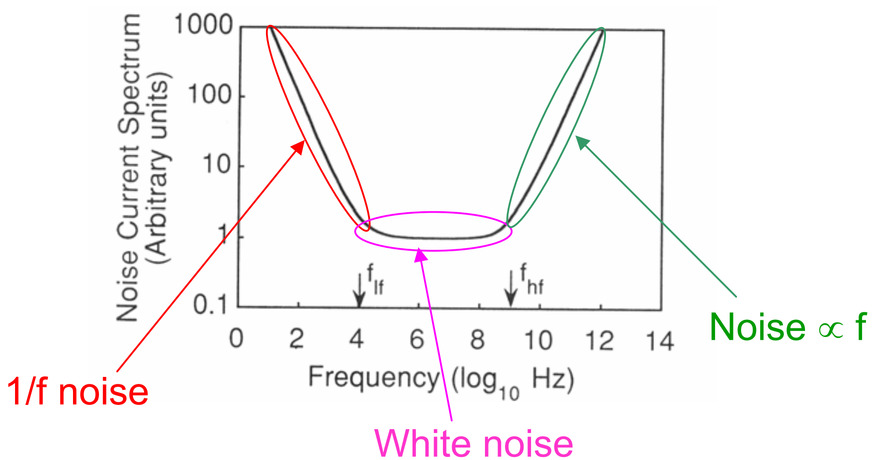
$$k = 1.38 \cdot 10^{-23} \; Joules / K$$

k is Boltzman constant
T is the temperature of the output resistance in K

ADDITIONAL THERMAL NOISE SOURCES

- Two main technological alternatives can be used in the implementation of front-end amplifiers: Field Effect Transistor (FET) or Bipolar Junctions Transistors (BJT)
- With both technologies additional additive thermal noise sources are introduced at the output of the amplifier:
  - "1/f noise" that decreases with frequency as 1/f and prevails in the range 0 to tens of kHz
  - A second term that is constant
  - A third term that increases with frequency as f, which can be neglected at common transmission rates

- Depending on the amplifier bandwidth (i.e. on the bit rate) one of these noise sources predominates



NOISE CHARACTERIZATION

At the input-referred point, that is right before the front-end amplifier, thermal noise is given by:

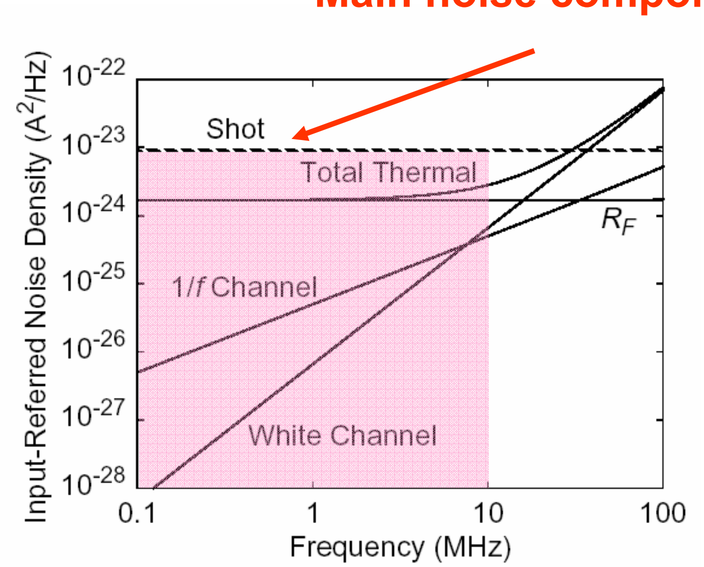
$$P_{thermal}(f) = \frac{2kT}{R} + g(f) + g\left(f^2\right)$$

The total input-referred noise PSD is:

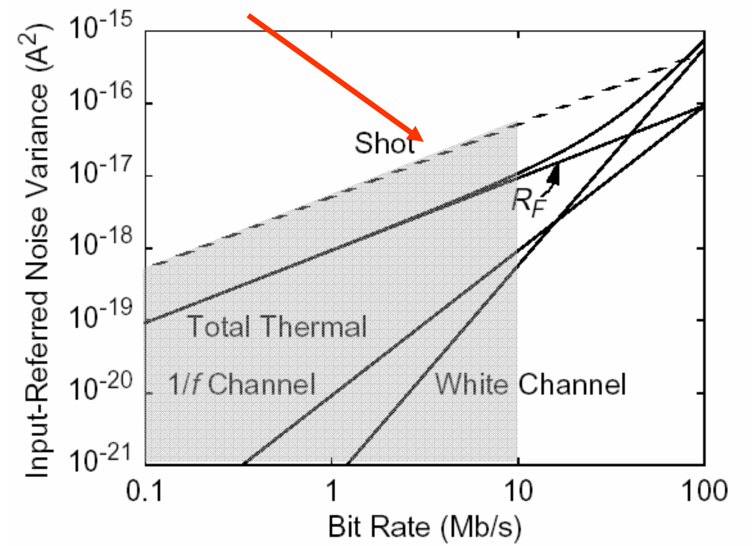
$$P(f) = P_{shot}(f) + P_{thermal}(f) = P_{shot}(f) + \frac{2kT}{R} + g(f) + g\left(f^2\right)$$

NOISE CHARACTERIZATION

Main noise component (for indoor applications)



Dominant input-referred noise power spectral densities (one-sided).

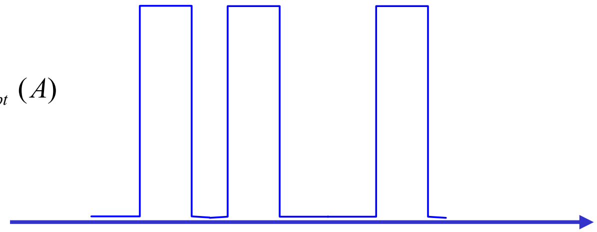


Dominant input-referred noise variances

For a regular indoor scenario, noise components can be reduced to shot noise at the receiver

SNR CHARACTERIZATION

$$2I = 2\rho P_{opt}\ (A)$$



$$BER = Q(\sqrt{SNR})$$

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{y^2}{2}}\,dy$$

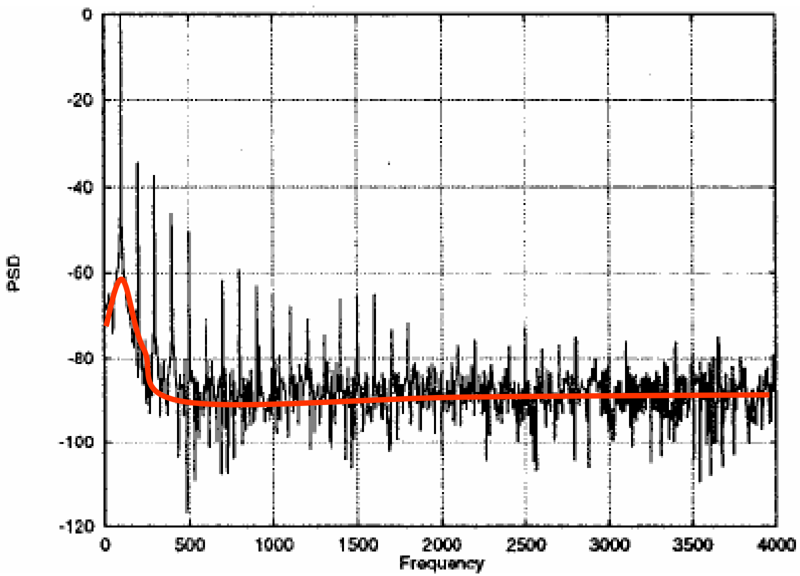
$$SNR = \frac{I^2}{\sigma_{tot}^2}$$

$$\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2$$

$$P_{shot}(f) = q\rho P_{interference}\ (A^2 / Hz)$$

Shot noise is calculated as a function of the noise sources present in the channel

INCANDESCENT LAMPS



Halogen and incandescent lamps have a similar behavior

The effect is similar to a 100 Hz sinusoid (over 800 Hz all components are 60 dB below the fundamental)

Typical electrical spectrum of a 60 W, 50 Hz tungsten-filament incandescent lamp. No optical filters have been used

INCANDESCENT LAMPS CHARACTERIZATION

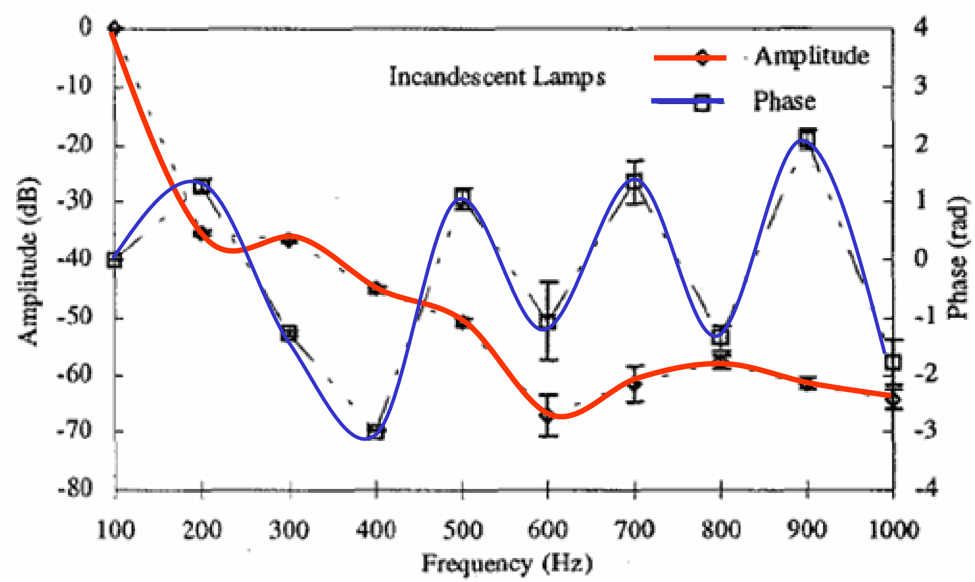
Relative amplitude and phase of each harmonic of 100 Hz

Background current

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

Parameter depending on the optical filter (for a typical high pass filter is 1.5, without filter is 1)

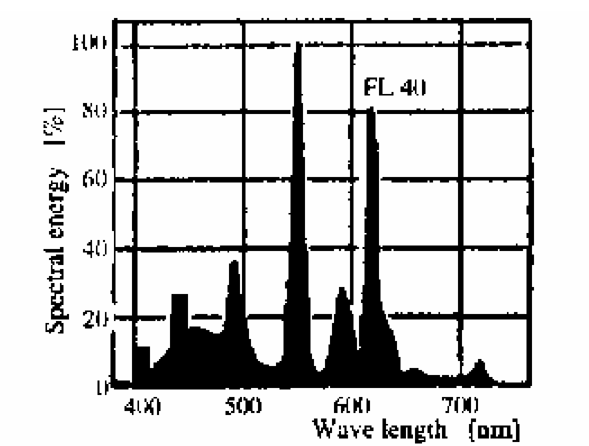
Relates the interference amplitude and average background current produced by average background irradiance (typically 8.7)

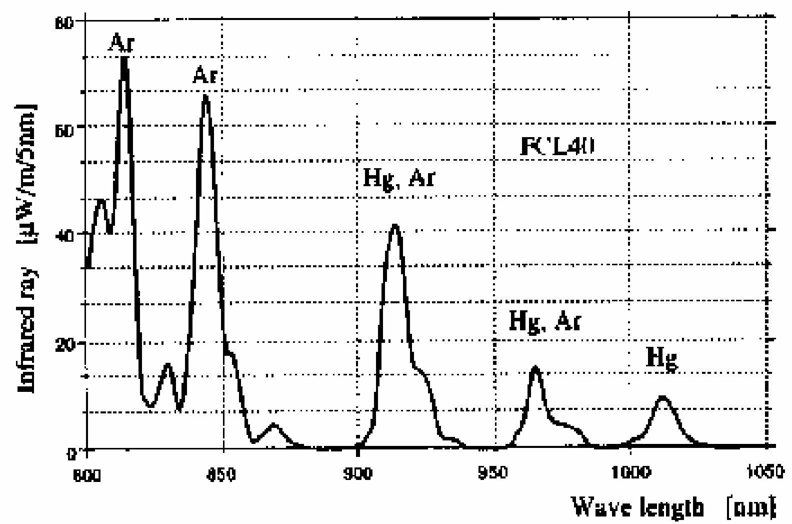


FLUORESCENT LAMPS

Fluorescent lamps emit strongly at spectral lines of mercury and argon that lie in the 780-950-nm band of interest for low-cost infrared systems.

Fluorescent lamps emission is modulated in a near-periodic fashion at the lamp drive frequency, and the detected electrical power spectrum contains discrete components at harmonics of the drive frequency (50 or 60 Hz).Their electrical spectrum has energy at harmonics up to tens of kilohertz.





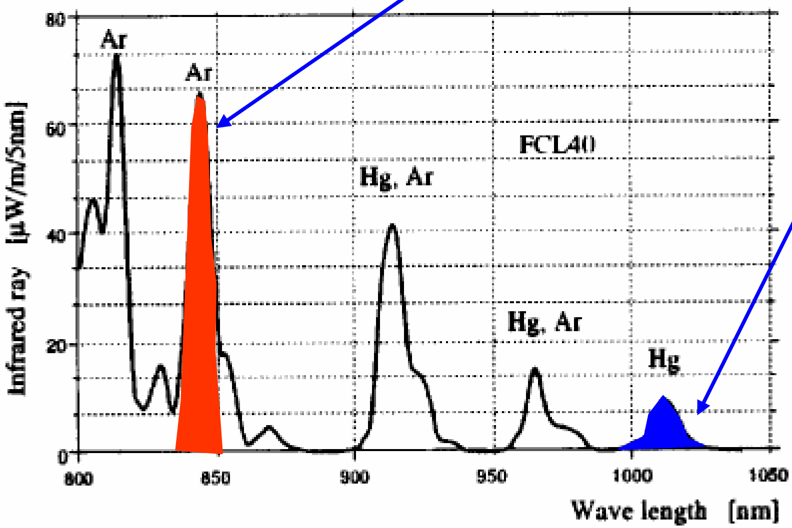
Left: emission in the visible spectrum

Right: emission in the infrared

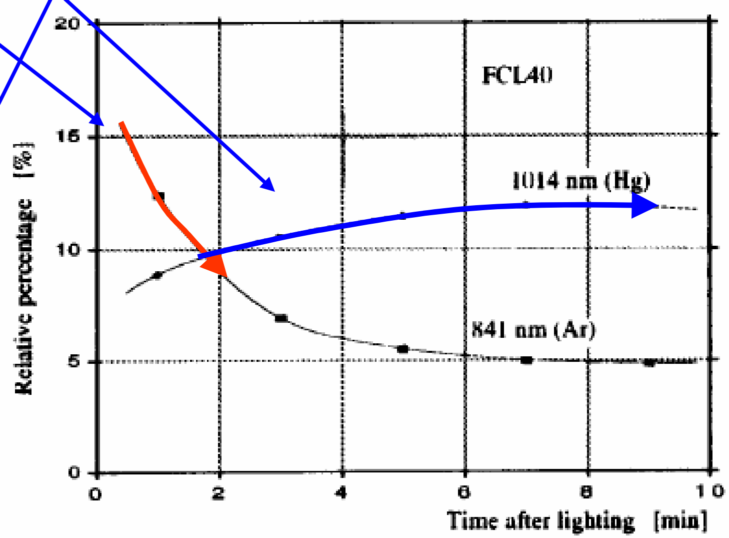
FLUORESCENT LAMPS

When switching, the effect of the Argon prevails (over the first transmission window)

After a while, the main effect is due to Hg (over the 2nd window)

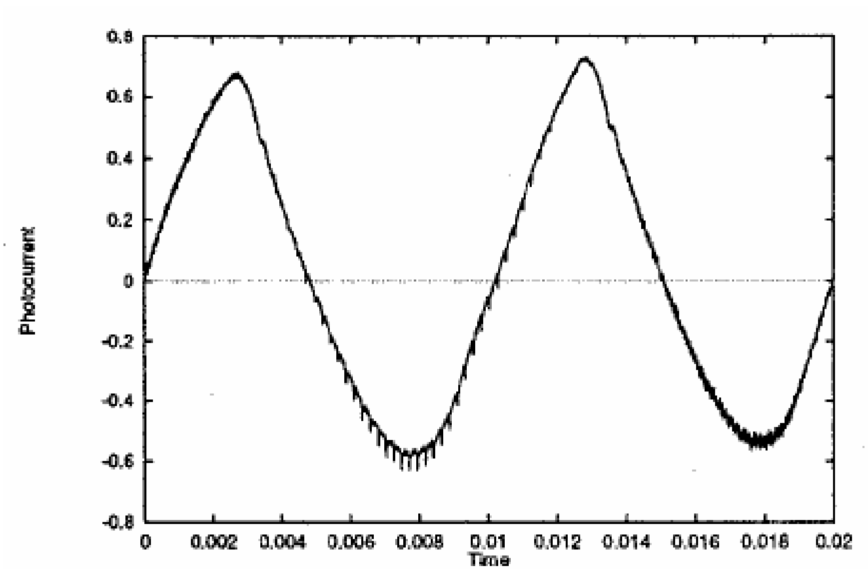


IR spectral distribution of a typical fluorescent lamp

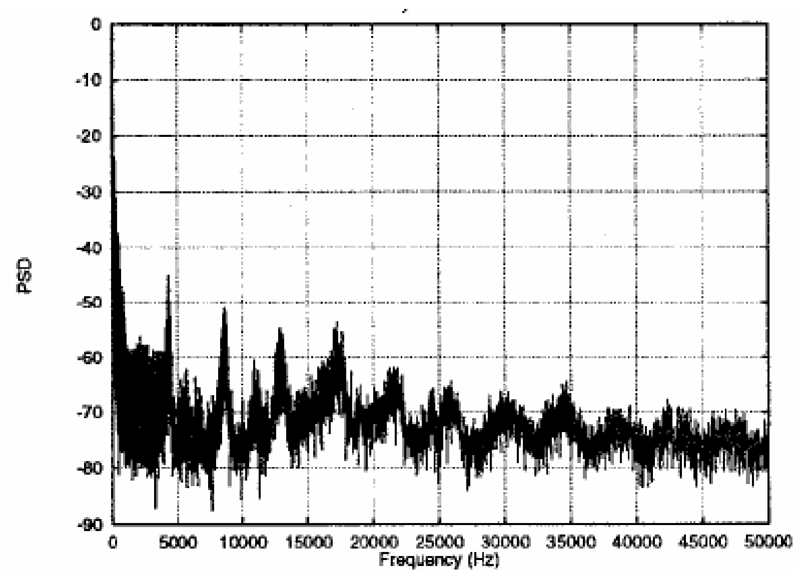


Time variation of IR spectral distribution of a typical fluorescent lamp

FLUORESCENT LAMPS INTERFERENCE



Time response



Spectral response

Interference current

FLUORESCENT LAMP CHARACTERIZATION (LOW FREQUENCIES)

The interference produced by different fluorescent lamps is very similar among lamps up to 2 kHz, but at higher frequencies each lamp has a different behavior

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

- i_{fluor}: i_{low}
- F_2: Parameter depending on the optical filter (for a typical high pass filter is 6, without filter is 1)
- A_2: typically 1.2 (empirical)
- $b_i \cdot \cos(2 \cdot \pi \cdot (100 \cdot i - 50) \cdot t + \varphi_i)$: Term for odd harmonics
- $c_i \cdot \cos(2 \cdot \pi \cdot 100 \cdot i \cdot t + \phi_i)$: Term for even harmonics

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

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

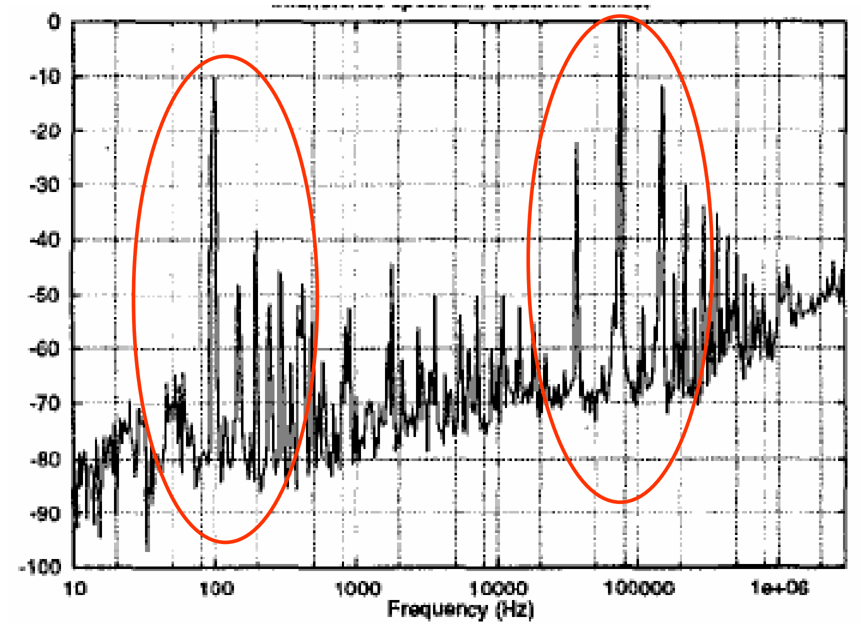
Model valid for conventional and electronic ballasts up to 2 kHz

ELECTRONIC BALLAST FOR FLUORESCENT LAMPS

High-efficiency "electronic ballasts" drive the lamps at frequencies of tens to hundreds of kilohertz. Their detected electrical spectrum contains energy up to hundreds of kilohertz.

These lamps cause potentially much more serious interference to infrared links.

The system penalty caused by fluorescent-light noise depends strongly on the modulation scheme employed.



Spectrum of the interference produced by fluorescent lamp geared by electronic ballast

Source: R. Narasimhan, M.D. Audeh and J.M. Kahn, "Effect of Electronic-Ballast Fluorescent Lighting on Wireless Infrared Links", *IEE Proceedings-Optoelectronics,* December 1996.

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FLUORESCENT LAMP - electronic ballast (HIGH FREQUENCIES)

I_{low} **was calculated before, the joint frequency response is**

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

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

Table valid for

f_{high}=37.5 kHz

- The parameters F_3 and A_4 are highly dependent on the ballast (and on the manufacturer)

Model valid only for electronic ballasts at high frequencies

j	d_j (dB)	θ_j (rad)	j	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

EFFECT OVER IR SIGNALS

- The effect of incandescent lamps is limited in frequency and can be easily mitigated
- Fluorescent lamps (especially when driven by electronic ballast) emit an infrared signal that is periodically modulated at rates of tens of kilohertz, and that can severely impair the performance of IR wireless links.
- This effect can be reduced by means of lenses and optical filtering or by coding and modulation

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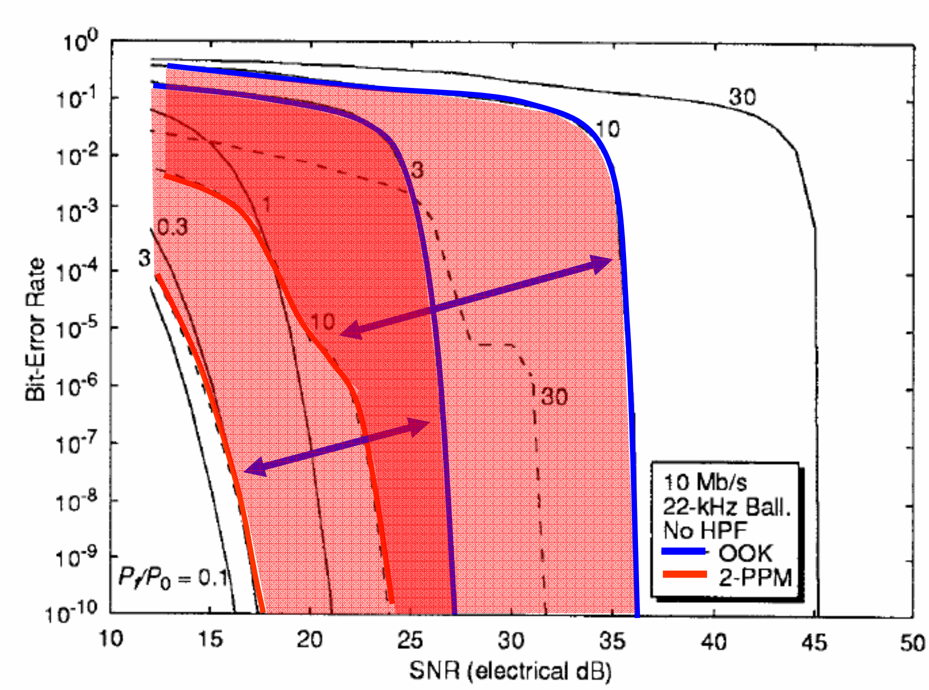
EFFECT OF FLUORESCENT LIGHT NOISE ON PERFORMANCE



BER curves for various ratios of P_f/P_0 for OOK and 2-PPM at 10 Mb/s. The fluorescent lamp is driven by a 22 kHz ballast and no highpass filter is employed

***P_f*:** Maximum absolute excursion (with respect to the mean) of the received fluorescent optical power waveform

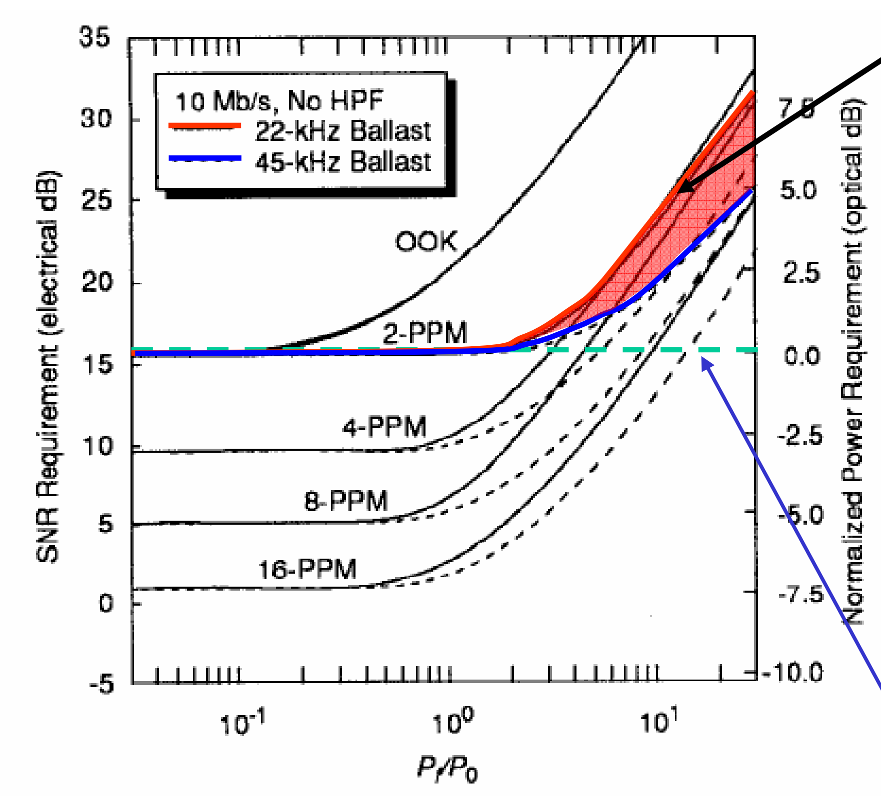
***P_0*:** Is defined as the average optical power required to achieve 10^{-9} BER with OOK in the absence of fluorescent Light

As P_f/P_0 increases there is an increase in the required SNR

OOK is degraded more rapidly than 2-PPM (due to DC components)

Source: R. Narasimhan *et al.* “Effect of electronic-ballast fluorescent lighting on wireless infrared links” IEEE ICC 96, June 1996 Pages:1213 - 1219 vol.2

EFFECT OF FLUORESCENT LIGHT NOISE ON PERFORMANCE

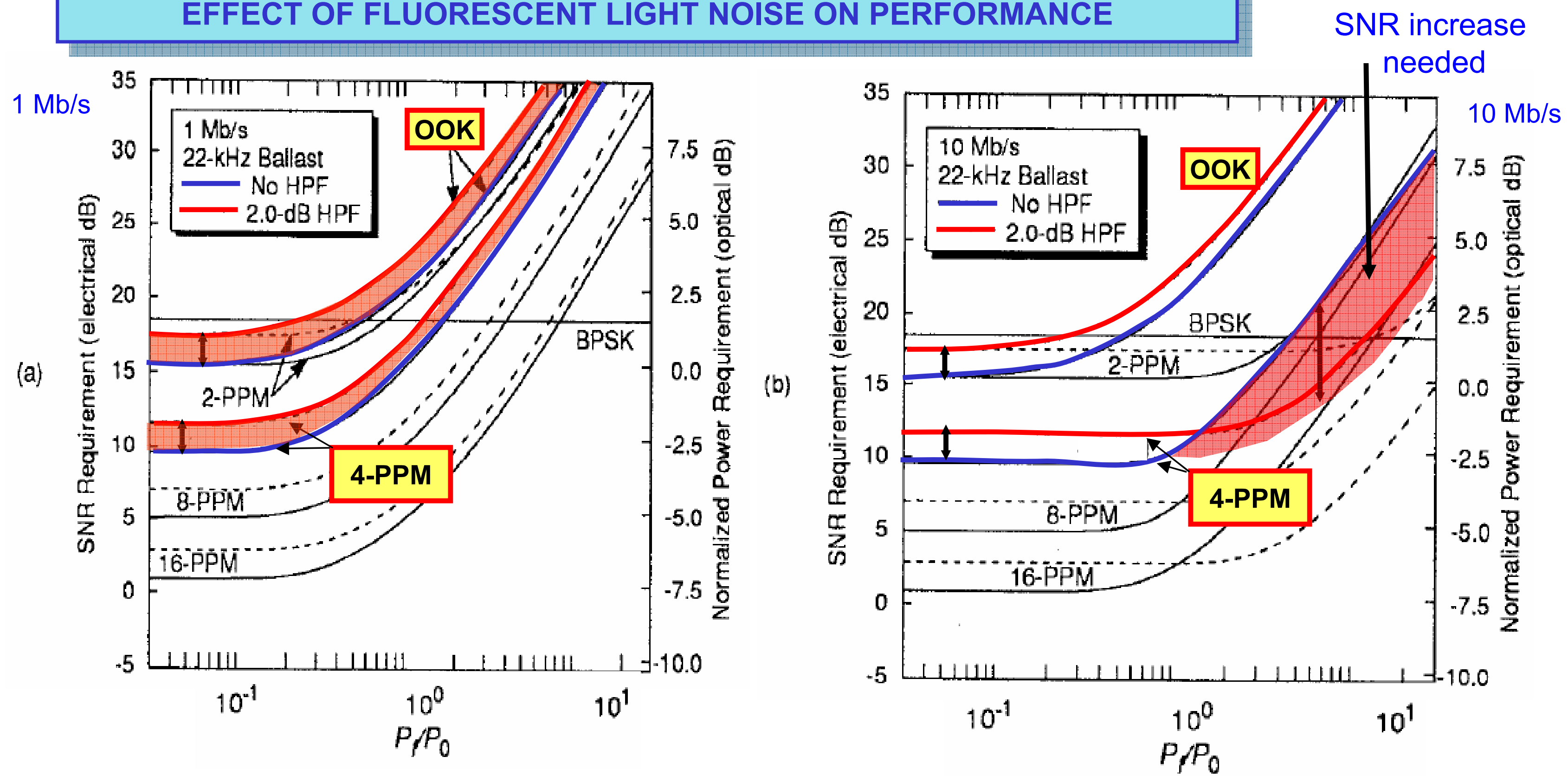


SNR and normalized optical power required to achieve 10^{-9} BER at 10 Mb/s versus P_f/P_0 with no highpass filter for 22 kHz and 45 kHz ballast

(0 dB corresponds to the P_0 power)

BER=10^{-9}

EFFECT OF FLUORESCENT LIGHT NOISE ON PERFORMANCE



SNR requirements and normalized optical power required to achieve 10^{-9} BER versus P_f/P_0 for 22 kHz with no highpass filter and with a highpass filter inducing a 2 dB SNR penalty

High pass filtering does not affect the performance on OOK!!
(but improves performance of PPM)

FURTHER READING

Vogel, W.J.; Hao Ling; Torrence, G.W.; “Fluorescent light interaction with personal communication signals” *IEEE Transactions on Communications,* Volume: 243, Issue: 234, Feb./ March/April 1995 Pages:194 –197

Moreira, A.J.C.; Valadas, R.T.; de Oliveira Duarte, A.M “Characterisation and modelling of artificial light interference in optical wireless communication systems”*;* PIMRC'95. Sixth IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 1995. Volume: 1, 27-29 Sept. 1995

Narasimhan, R.; Audeh, M.D.; Kahn, J.M.; “Effect of electronic-ballast fluorescent lighting on wireless infrared links”, IEEE International Conference on Communications, Volume: 2 , 23-27 June 1996 Pages:1213 - 1219 vol.2