Characterisation and Interference Model of Contemporary Artificial Light Sources Noise on a VLC channel

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***Abstract*—Indoor visible light communication (VLC) has seen major growth in the last decade, reaching data rates in the Gbps range over 10 m distance. Its main limiting factors however are the low speed of the optoelectronic devices as well as the ambient noise reducing the system performance and reliability. The interference due to the artificial white light sources used for illumination in an indoor environment is one of the major noise sources challenging the performance of the VLC indoor channel. Since these noise sources operate at different frequencies, filtering their DC effect out does not eliminate their effect. This paper practically measures the noise power of the contemporary artificial light sources in an indoor visible light link to characterize their effect. The measurements show that thermal light sources cause a high noise power in a limited bandwidth of a few hundreds of Hz, while gas discharge lamps and dimmed semiconductor light sources have a much wider significant noise spectrum. An interference model to determine the overall noise power due to said sources is then deduced.**

Keywords—Visible light communications, noise, artificial light sources, interference model

I. Introduction

With the ever increasing demand of devices connectivity and the rise of Internet of Things (IoT), the bandwidth for transmitting those huge amounts of data is becoming scarcer every day. While the radio frequency (RF) spectrum has reached its limits by offering frequencies up to 300 GHz, optical wireless technologies offer a free and unlicensed spectrum that is 1000 times wider than that of the RF spectrum. Therefore, optical wireless communication and especially visible light communication (VLC) has seen a major growth and lots of potential in the past decade [1]–[4].

In VLC, modulated light transmitted from a light emitting diode (LED) carries the transmitted data and propagates through a free space channel towards a photodiode. This converts the signal back into an electrical form to be demodulated by the receiver circuitry. The idea of piggybacking data on the readily available high brightness LEDs used as light sources for illumination results in a communication technology that operates on nearly no additional power or cost. The uplink can then be based on an infrared (IR) link that offers high speed connectivity without illumination [2].

Besides its free spectrum, low cost and low power consumption, VLC causes no health hazard and is immune to eavesdropping and RF interference. Due to the fact that a VLC cell is limited in space to be confined in a single room, the technology is considered secure and the transmission frequencies can be reused for multiple users more frequently than with RF technologies. VLC can therefore replace regular RF technologies with higher efficiency in the fields of inter-vehicular communications, interference-sensitive environments such as hospitals and airplanes as well as in cyber-secure wireless networks [1].

Published research on VLC has demonstrated its feasibility in indoor environments for line-of-sight (LoS) as well as non-LoS links with data rates up to 1.1 Gbps at distances of 10 m between transmitter and receiver [1], [3], [5]. The average signal-to-noise ratio (SNR) measured at desk height is between 40 dB and 60 dB and is mainly affected by the ambient noise sources in the visible light range [1]. The data rate, maximum distance between transmitter and receiver as well as the SNR are all affected by the overall noise and interference in the indoor VLC link. The sources of noise in a VLC system have been reported to be mainly due to thermal noise and shot noise. Both types of noise have been estimated to be stationary random processes whose variance is non-varying in time [6].

Thermal noise arises in the electrical part of the receiver circuit due to the collision of electrons in conducting materials of a certain resistance at a certain temperature. It is irrelevant of the incident optical power and is estimated as a white Gaussian noise with zero mean. Its variance is proportional to the operating temperature and drops with increasing resistance [6].

Shot noise on the other hand is caused due to the variation of the number of photons that are incident on the photodetector active area. It increases proportional to the square root of the incident optical power and depends on the bandwidth of the used electrical filter. Since shot noise is irrelevant of the light source, ambient background light has a major effect on the increase of the shot noise and causes therefore a dramatic reduction in the VLC link performance [6].

Sun light causes a constant interfering signal in the form of a DC value on a VLC channel that is outside of the modulation bandwidth and can be easily filtered out. As long as sun light does not saturate the photodiode, it only causes a minor and solvable problem [1]. Artificial light sources driven by mains frequency and more sophisticated electronic drivers, however, cause a time-varying interference signal that is not so easy to avoid. The interference due to the artificial light sources has a twofold effect on the overall noise detected by a photodetector. First, artificial light sources increase the induced shot noise, which is proportional to the measured DC current at the output of the photodiode, due to the steady component of irradiance. Second, they produce a time-varying interference signal due to their driver circuits being fed by the mains power supply which results in an optical power penalty [7].

The time-varying component of interference caused by artificial light sources in the communication environment however have been mentioned in published literature, but never accounted for in the overall noise power. Moreira et al. have studied and characterized the effect of the interfering light signals from fluorescent lights and incandescent lamps on the infrared (IR) communication link, however, the effect of more modern and contemporary white light sources such as white LEDs, dimmable LEDs and energy saving light bulbs on the visible light communication channel was not addressed [5], [7]. A. C. Boucouvalas has displayed the spectra of a wider variety of interfering artificial light sources on indoor wireless optical links in the IR range including tungsten light bulbs, IR headphones and TV remote controls as well as non-time-varying daylight [8].

In order to characterize the effect of those two forms, the artificial light sources need to be grouped according to their lightning technology and tested separately in the time and frequency domain. There are 3 groups of light sources used nowadays for illumination: thermal light sources, gas discharge lamps and semiconductor light sources [9].

This paper practically measures the noise and interference power of the contemporary white light sources in each category with the focus on the VLC channel. It then compares the effect of those sources in terms of DC power, noise variance and effective bandwidth and analyses the experimental results to introduce an interference model for each of those sources. This can be employed in the determination of the channel characteristics and the created noise profile highlights the modulation frequencies with the least interference. To our knowledge, the noise and interference of the contemporary noise sources have not been studied before.

The next section describes how the ambient light sources are characterized and the measurement setup used to obtain the practical results. The results for each light source are displayed in section III while section IV summarizes the practical measurements and compares the light sources. Section V introduces the mathematical interference model and Section VI concludes the paper.

II. Measurement setup

The noise source of interest for the experiment is the artificial white light sources (in the range between 400 to 700 nm) that are used for illumination in domestic areas and workplaces. Hence, a generic source driver connected to the mains supply (220 V, 50 Hz) is used on the transmitter end of the link to switch on the noise source. Since the maximum noise power is captured at minimum distance from the receiver and decays with the inverse square root of the distance, a 1 m distance between the noise source and the detector insures that most noise power is captured and a worst case scenario is achieved. Moreover, to ensure that the receiver is directly facing the light source with 0° angle between their axes, a practical rail is placed between the link ends. At the receiving end, an optical power and energy meter (Thorlabs PM200) is used to measure the power of the emitted light source. The high sensitivity silicon PIN photodiode (PM16-121C) attached to the meter covers the visible light wavelengths range. It has a response time of less than 1 μs allowing variations of frequencies up to 1 MHz to be measured, which is sufficient for the experiment. The output of the meter is displayed by a PC oscilloscope (Picoscope 6402D) and the spectrum is determined by a fast Fourier transform, resulting in the power spectral density (PSD) curve. All measurements are taken in a dark room to eliminate all ambient noise sources. The measuring probes are grounded with the oscilloscope casing to avoid electromagnetic interference caused by ground loops. Fig. 1 shows a block diagram of the measurement setup. To verify the results, each measurement is repeated five times.

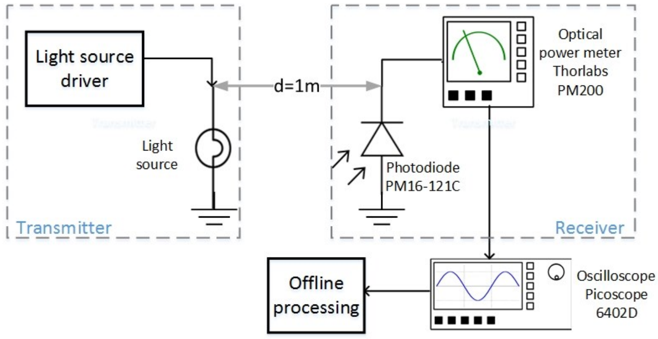

Fig. 1 Block diagram of the practical measurement setup

III. Results

Thermal light sources

Thermal light sources depend on current flowing through a very thin filament inside a vacuum in the light bulb. The flowing current heats the filament to the point of glowing, producing thereby light and large amounts of heat. This type of lamps has a very low luminous efficiency as well as low life-time due to the high amount of produced heat and are therefore banned (except for the most energy-efficient versions of them) from the European Union. Nevertheless, this type of lamp is still widely used in non-EU countries in both retail and domestic areas [9]. Thermal light sources are also called incandescent and include but are not limited to Tungsten light bulbs.

The light power emitted from a Philips® 248872 Soft White 65-Watt bulb is shown in Fig. 2. The waveform is an almost perfect sine wave with period of 10 ms, peak-to-peak voltage of 189 mV, DC shifted to 1.339 V. Those voltage

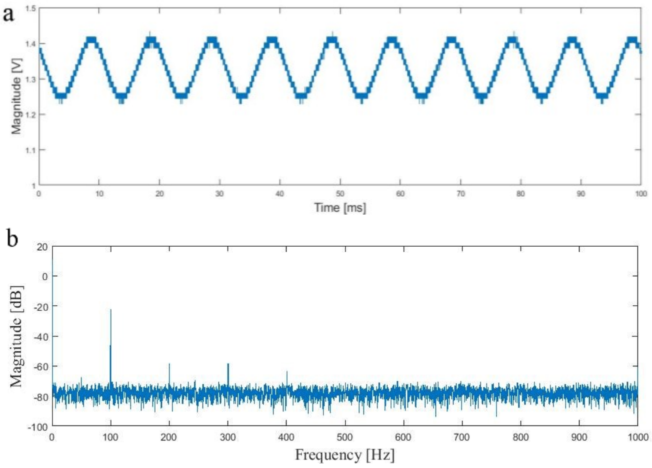

Fig. 2 Time wave (a) and spectrum (b) of the light power of an incandescent light bulb, captured on the PC oscilloscope

values can be converted to a 0.281 mW peak-to-peak variation with an average power of 1.00425 mW according to the equation:

$$V_{out} = 2V \times \frac{measuredValue}{fullScaleValue} \quad (1)$$

The corresponding frequency response shown in Fig. 2 shows peaks only at harmonics of the 100 Hz component until 300 Hz. According to Moreira *et. al*, magnitudes below 60 dB of the fundamental component are considered insignificant [6], hence a threshold of -60 dB relative to the fundamental magnitude is considered the limit throughout the experiments in this paper. Hence, frequencies other than 100 Hz for the Tungsten lamp can be neglected as shown in Fig. 2. The variance σ^2 of the noise can be calculated as

$$\sigma^2 = \int_{-\infty}^{\infty} (PSD) df - \mu^2 \quad (2)$$

where μ is the mean of the signal, in this case the average DC value. Based on equation (2), the variance of the Tungsten light bulb is 0.82 mW.

Gas discharge lamps

Gas discharge lamps make use of an alternating electric field between two electrodes placed at both ends of a gas-filled discharge tube to create ultra-violet light. This light is then converted via a fluorescent coating to visible light. Although these lamps have a higher luminous efficiency and life time than incandescent light bulbs, they produce a lower colour rendering of light and are therefore used mainly for efficient wide-area lighting. Types of gas discharge lamps include, but are not limited to, fluorescent light bulbs, energy saving light bulbs and compact fluorescent lamps [9].

A ballast drives the alternating AC field responsible for controlling the gas molecules in the discharging tube. Older versions of gas discharge lamps were driven by conventional ballast and are of lower efficiency than contemporary gas discharge lamps that are driven by electronic ballast. They are therefore replaced nowadays with the more efficient electronic

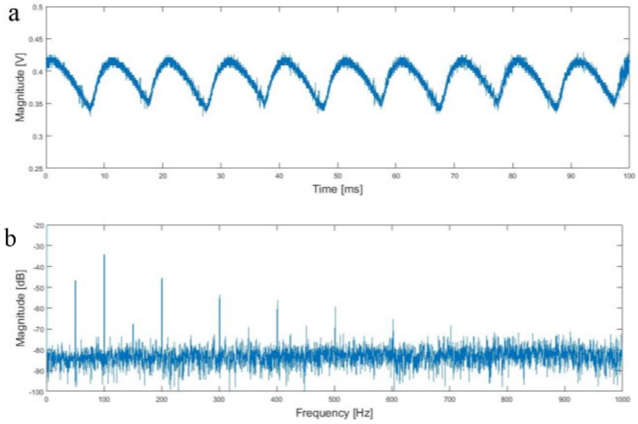

Fig. 3 Time wave (a) and 100 kHz spectrum (b) of the light power of the Philips energy saving light bulb

ballast gas discharge lamps, which have a higher switching frequency in the range between 20 kHz and 40 kHz [8].

For this experiment, a Philips® energy saving warm white light bulb (Tornado®) of power 23W, producing 1550 lm of luminous flux with a luminous efficiency of 67 lm/W is tested. The light source is driven with mains power and a current of 170 mA. The measured power is a distorted sinusoid with period 10 ms, DC shifted to 28.6 μW. The peak-to-peak amplitude of the periodic power signal is 7.09 μW as shown in Fig. 3. The line constituting the sine wave consists of tiny periodic sinusoidal waves of period 100 μs which are equivalent to a 10 kHz variation in frequency. This frequency component is due to the high frequency switching of the electronic ballast driving the lamp. Accordingly, the power spectral density has a low frequency range shown as harmonics of 100 Hz until 500 Hz besides the 50 Hz mains frequency as well as a high frequency component of harmonics of the 10 kHz at 20 kHz and 40 kHz with decaying amplitude.

Semiconductor light sources - 3-way LED

The LEDs belong to the group of semiconductor light sources. White LEDs used for illumination either consist of a combination of red, green and blue (RGB) LEDs or of a blue LED with a yellow phosphorus coating. The combination of those colours trick the human eye to see the resulting light as white. Although the LEDs as components can only produce light when a DC current flows through them, they can be used in an AC network when powered via a DC converter. Nowadays, LEDs are the most popular lighting solution because of their exceptionally long life-time and high luminous efficiency compared to other lighting alternatives. Some LEDs are not dimmable due to their manufacturing process, but instead have a 3-level brightness switch, via which the user can control the luminous flux. The internal structure of such a 3-way LED lamp is composed of two independently controlled LEDs with different power levels. To achieve lowest light intensity, only the lower power LED is switched on. For medium intensity, the higher power LED would be the only source of illumination. Both LEDs are simultaneously lit for the maximum required intensity. For the sake of this

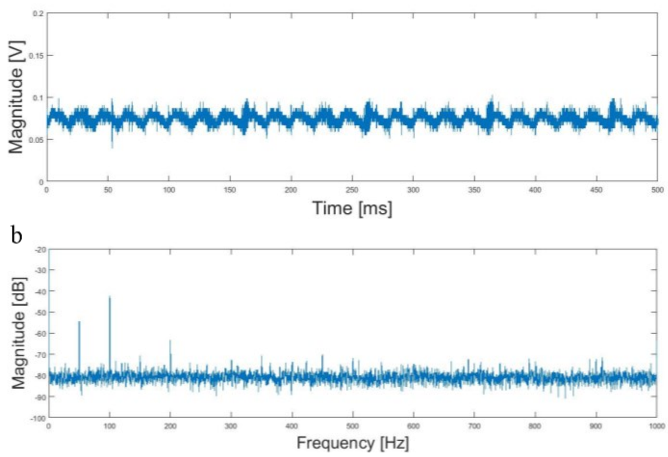

Fig. 4 Noise power in time domain (a) and frequency domain (b) of a 3-way LED on lowest intensity

experiment, all three levels of the 3-way light bulb have been investigated separately.

The 3-way LED (Venus®) bulb tested in this experiment operates with mains supply. It produces light of 6500 K colour temperature and consumes just 9W to produce 806 lm bright light. The three adjustable brightness steps yield 15%, 40% and 100% of the maximum luminous flux, respectively.

a

First, the light power is measured when the LED is set at lowest intensity. The noise power shows resemblance to a full-wave-rectified sinusoid with 20 ms period and a peak-to-peak variation of only 2.25 μW. The fluctuations shown in Fig. 4 magnitude as well as the full-wave-rectified shape of the periodic signal result from the AC to DC conversion and its capacitor smoothing effect. This smoothing effect is also obvious in the frequency domain illustrated in Fig. 4 b. The significant peaks of the spectrum are only at 50 Hz and 100 Hz. The variance is therefore 98.1 μW.

The time and frequency response of all three light intensities of this source are similar except for their DC shifts and the harmonics amplitudes, respectively.

Semiconductor light sources - dimmable LED

An LED is inherently not dimmable because the light brightness it outputs does not depend on the input voltage after the switch-on threshold. However, lightning manufacturers have overcome the non-dimmable property of LEDs by employing pulse width modulation (PWM) or analogue dimming techniques. Since the human eye cannot detect flickering of frequencies higher than 50 Hz, the quick on-off switching of the pulse width modulated LED is not noticeable by users [6] but only by the photodetector at the receiver end. The analogue dimming technique on the other hand works on reducing the LED forward current to reduce its intensity. While this option is favourable in terms of power efficiency and LED life time, it might produce disturbances in the lightning quality of the LED. This type of dimming is expected to have the same effect on the interference with a visible light communication system as a regular LED with AC to DC converter [7].

In this experiment an IKEA® dimmable transparent LED is used. It produces a maximum of 600 lm at 8.6 W. The dimmable LED uses the mains power and 64 mA current. The experiment is repeated at minimum and maximum intensities employing an off-the-shelf LED dimmer. This dimmer causes the LED driver to use PWM with duty cycles varying according to the dimming level.

The resulting power is similar to the 3-way LED at maximum intensity. The distorted sinusoidal wave has a period of 10 ms, a peak-to-peak variation of 11.25 µW with a DC average of 32.8 μW and variance 95.5 μW. The frequency spectrum of the signal shows significant peaks only at 50 Hz, 100 Hz and 200 Hz with a flat spectrum thereafter, illustrated in Fig. 5.

The spectrum of the lowest intensity (i.e. at maximum dimmable level before complete off-switching) shows the effect of the flickering due to PWM. Compared to the high intensity spectrum, the relative amplitudes of the low frequency harmonics (below the 1 kHz) are higher and the width of the

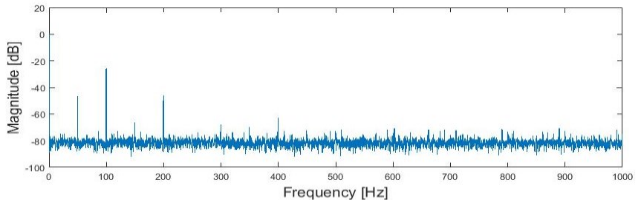

Fig. 5 Spectrum of a dimmable LED light bulb at maximum brightness

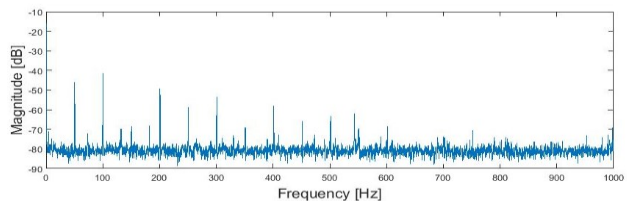

Fig. 6 Spectrum of a dimmable LED light bulb at maximum brightness

spectrum reaches is larger, reaching 1 kHz as opposed to only 200 Hz without dimming.

IV. Results Summary

In this section, the paper compares the impact of all four contemporary lights as sources of interference. From all investigated sources in the previous section, the incandescent source exhibits the highest DC power, almost ten times higher than the other sources. On the other hand, due to its simple design and manufacturing process, it offers the lowest number of harmonics and can easily be eliminated using a high pass filter (above 100 Hz) at the receiver end. The noise of the other three sources show similar power values at the 1m channel distance as displayed in Fig. 7.

The noise spectrum band and the number of frequency harmonics of a light source define to a great extent its noise characteristics. They determine the modulating frequency of the transmitting LED and help design the filter cut-off frequency. A comparison between the measured noise power spectral densities is summarised in Fig. 8. The obtained results show that the dimmable LED and the lowest intensity of the 3-way LED produce maximum harmonics and the widest noise spectrum. On the other hand, the Tungsten light source

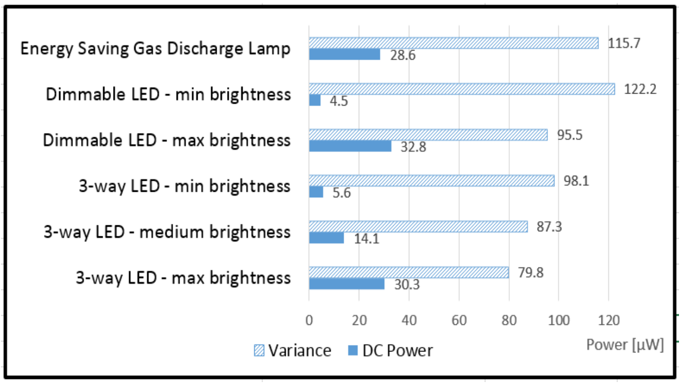

Fig. 7 DC power and variances of light sources at 1 m distance

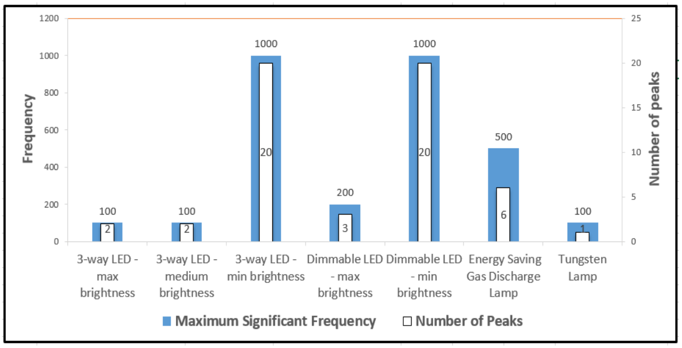

Fig. 8 Low frequency interference spectrum properties of the different light sources.

provides the narrowest spectrum with the least number of significant harmonics. Although the energy saving lamp has a low-frequency noise spectrum of only 500 Hz, its high frequency noise response (at 10k Hz, 20 kHz and 40 kHz) should be filtered or taken into consideration when designing an indoor VLC system.

To conclude, dimmed LED sources cause the widest noise frequency spectrum while the old lighting solutions deliver a higher DC value on a narrower frequency band, seen in Fig. 7.

V. Interference Analysis and Modelling

In order to calculate the power penalty caused by the above mentioned interference sources, an interference model is required. This section introduces a simple interference model for each of the four artificial light sources.

The optical power detected by the photodetector consists of a constant background power P_B and a time-varying interference power $P_{interf}(t)$ due to the periodic signals from the artificial light sources [10].

$$P_{opt}(t) = P_{interf}(t) + P_B \tag{3}$$

This incident optical power generates three different noise components: a background shot noise $P_{B\_shot\_noise}$ due to the photocurrent generated by P_B, an interference noise component equal to $P_{interf}(t)$ as well as a time-varying shot noise component $P_{interf\_shot\_noise}(t)$ due to the varying photocurrent caused by $P_{interf}(t)$. Hence, the overall noise power is [6]:

$$P_{noise}(t) = P_{interf}(t) + P_{B\_shot\_noise} + P_{interf\_shot\_noise}(t) \tag{4}$$

The responsivity R of a photodiode is defined as the output photocurrent I_P relative to the incident optical power P_{opt}.

$$R = \frac{I_P}{P_{opt}} \tag{5}$$

The average value of the shot noise power of a non-varying shot noise is defined as

$$\sigma^2_{shot\_noise} = 2\,q\,<i>\,B \tag{6}$$

where q is the electric charge of an electron, $<i>$ is the average generated photocurrent and B is the bandwidth of the electrical filter in the detector circuit [6].

Hence the shot noise power components are related to the measured power signals by:

$$P_{B-shot\_noise} = 2\,q\,R\,P_B B \tag{7}$$

Since the interference power signal produced by the artificial noise sources is a periodic and deterministic signal, $P_{interf}(t)$ can be described by its Fourier series components as follows:

$$P_{interf}(t) = a_0 + \sum_{i=1}^{i_{max}} a_i \cos(2\pi(100i-50)t) + b_i \cos(2\pi(100i)t) \tag{8}$$

where a_0 is the average DC value, a_i and b_i are the amplitudes of the 50 Hz and 100 Hz harmonics respectively and i_{max} is the number of the maximum significant harmonic. Since not all the harmonics are significant in our noise calculation, only those that are less than 60dB below the fundamental amplitude will be taken into consideration when substituting in the above equation [7].

A MATLAB® program has been designed to extract the magnitudes of the significant peaks in frequency spectra of each noise source. The background noise power P_B is calculated from the DC average (DC shift) of the time domain waveform. The results of the parameters for the measurements for each artificial light source are summarized in Table 1, where a_i, b_i and P_B are in μW.

In the case of electronic ballast fluorescent lights, the interference model should take into consideration both the low frequency and high frequency components of the measured spectrum. The overall optical power of the interfering signal can then be calculated as [7]:

$$P_{interf}(t) = P_{interf\_low}(t) + P_{interf\_high}(t) \tag{9}$$

Table 1 Parameter values for each light source

Light Source	i	a_i	b_i	P_B
Incandescent	1	0	4.1	1004.25
Energy Saving	1	0.001648	0.028697	28.6
	2	0	0.0022	
	3	0	0.000336	
	4	0	0.000173	
	5	0	8.55E-05	
3-way LED - max	1	0.000281	0.004322	30.3
3-way LED - med	1	0.000166	0.000148	14.06
3-way LED - min	1	0.001709	0.000145	5.58
	2	1.15E-05	2.32E-05	
	3	0	3.7E-06	
	4	1.19E-05	6.28E-06	
	5	8.09E-06	0	
	6	0	3.97E-06	
	7	4.17E-06	0	
	8	4.25E-06	0	
	9	3.76E-06	0	
	10	3.63E-06	4.55E-06	
Dimmable LED - max	1	0.001702	0.204405	32.8
	2	0	0.001878	
Dimmable LED - min	1	0.001876	0.005158	4.5
	2	1.03E-05	0.000911	
	3	9.67E-05	0.000328	
	4	9.43E-06	0.000119	
	5	1.93E-05	3.44E-05	
	6	8.24E-06	1.01E-05	
	7	0	3.14E-06	
	8	6.9E-06	2.09E-06	
	9	0	1.89E-06	
	10	3.5E-06	8.91E-06	

Each of those terms is converted to its Fourier series components separately. While the low frequency component consists of a deterministic periodic signal at harmonics of up to 500 Hz described with equation (7), the high frequency component is of a more random nature and differs amongst different light bulbs of different manufacturers [6]. The mathematical expression of the high frequency component is:

$$P_{interf\_high}(t) = \sum_{i=1}^{\infty} c_i \cos(2\pi f_i t) \tag{10}$$

where c_i is the amplitude (in μW) and f_i is the frequency of each component respectively. The high frequency Fourier series parameters for the fluorescent energy saving light bulb are summarized in Table 2.

Table 2 Parameter values for the high frequency components of the energy saving light bulb

i	c_i	f_i
1	8.91E-05	3.7 kHz
2	0.001804	5 kHz
3	0.000183	8.4 kHz
4	0.000191	8.5 kHz
5	0.00031	8.65 kHz
6	0.000296	8.8 kHz
7	0.207072	10 kHz
8	0.002056	20 kHz

VI. Conclusion

In this paper the interference of artificial light sources and its effect on the overall noise has been measured and modelled. Four different light sources that are contemporarily used have been tested: a thermal light source, a gas discharge lamp and two semiconductor light sources (3-way LEDs and dimmable LEDs). The effect of the artificial light sources on the noise of an indoor VLC system is twofold: first, a constant increase in the shot noise is caused by the background non-varying power component and second, a time-varying increase in the shot noise and in the overall noise power is caused due to the deterministic periodic power due to the driving circuitry of the power sources. While the thermal source causes the highest background noise power, its frequency spectrum fades quickly to a flat response for frequencies above 100 Hz. Gas discharge lamps however have a higher effect on the overall noise showing high amplitudes of interference at low frequencies up to 500 Hz, besides significant high frequency noise components at frequencies up to 40 kHz. The most power efficient semiconductor light sources show significant noise components up to 1 kHz only when dimmed or at a low brightness setting due to the on-off-switching of the PWM-based dimming driver. The interference model describes the power spectral densities of each of the tested noise sources in terms of a Fourier series, which represents overall interference noise power in a VLC indoor system.

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