A Simplistic Channel Model for Cascaded PLC-VLC Systems

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***Abstract*—In this a paper, we propose a simplistic channel model for cascaded PLC-VLC system which highlights the noise scenario in such hybrid systems. The model utilises previously proposed channel transfer functions of both PLC and VLC channels and highlights the effects of the LED supply in the system. The noise scenario implemented on the model is based on the observations obtained from a practical measurement of PLC and VLC noise amplitude spectrum (NAS). The PLC-VLC channel is generalised and then simulated based on realistic data. In our results, we highlight the effect of the model's parameters and noise present in both PLC and VLC channels.**

keywords— *Channel model, cascaded PLC-VLC, PLC and VLC channels, Noise Effects.*

I. Introduction

Hybrid power line communication (PLC) and visible light communication (VLC) is a promising hybrid technology. Since its introduction by Komine *et al* in [1], it is evolving as a candidate for low-data applications [2] and high-data ones, such as in broadband broadcasting systems [3] and indoor hospital applications [4]. In PLC-VLC hybrid systems, the PLC technology is used as a backbone for the communication infrastructure and VLC technology makes provision of transforming a PLC signal into a wireless one [5]. Moreover, the combination of PLC and VLC technology is ubiquitous in nature; PLC utilises existing power line cables for both power and information distribution while VLC technology takes advantage of light emitting diode (LED) for both illumination and data provision.

With enormous research progress and achievements in solid state lighting, LEDs have gradually been used as replacement to incandescent and halogen bulb, for general purpose illumination applications. VLC exploits their fast switching properties [5], [6], to modulate the light and convey information through the visible portion of the electromagnetic spectrum. VLC is a short-distance wireless optical technology and therefore, inherits some of their properties and characteristics. The VLC channel exhibits multipath effects due to the Line of sight (LOS) and non line of sight (NLOS) path used to characterise its channel as elaborated in [7], [8].

In general, channel modelling in PLC can be done by bottom-up [9] or top-down [10], [11] approaches. The bottom-up approach treats the PLC channel as a black-box, analyse responses by fitting results from measurements and uses transmission line theory in order to produce the PLC channel transfer function [9], [12], [13]. Whereas in to top-down use high level abstraction with measured parameters [13] to characterise the PLC channel.

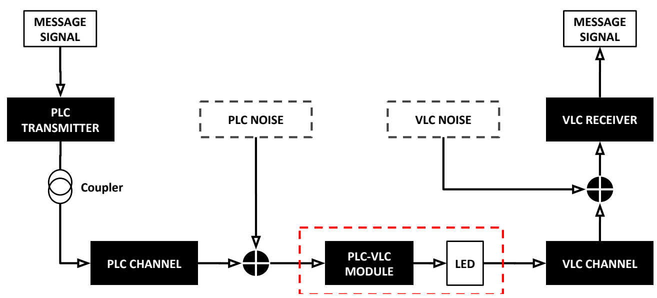


Fig. 1. Communication block diagram of a hybrid PLC-VLC system

Fig. 1 shows the overall block diagram for a hybrid PLC-VLC system. Being an integrated system, the signal is affected by noise present in both PLC and VLC channels. Interference and noise issues are inherently present in the PLC environment which is also highly frequency selective and time variant.

Integration of PLC and VLC is done by either decoding-and-forward (DF) or amplify-and-forward (AF) [14] using a PLC-VLC module [3]. The AF scheme consist of cascading both channels, without demodulation between both channels. This provides less complexity and change in the structure and of the LED. In most of the PLC-VLC work presented [3], [4], [15], [16], less attention is given on the channel modelling as they all assume a superimposition of both channels based on previously proposed models for individual PLC and VLC channels.

In this paper, we place our attention and proposal of modelling the PLC-VLC channel, based on previously proposed models and our channel measurements. Our model includes the effect of the LED supply, in the hybrid PLC-VLC channel. The LED driver, is the link between individual PLC and VLC domains. Due to its connection between both channels, it influences the behaviour of the overall channel model, and ought to be taken into consideration, when modelling the cascaded channel.

The rest of this paper is organised as follows. In Section II, we review the channels and LED supply. Section III presents the practical experiment illustrating the effect of the LED supply on the measured CFR. We then present the PLC-VLC channel model in section IV. Section V discusses the results obtain and the conclusion is given in section VI.

II. Theoretical Background

A. The PLC Channel

The PLC channel is a multipath, time and frequency variant environment. It is also characterised by considerable noise, impedance variation, and high attenuation. Therefore, the PLC channel is difficult to model due to its time and frequency dependence. The channel is hence, generally described as random, time-varying and with a frequency-dependent signal-to-noise ratio over a certain bandwidth [17].

Zimmermann and Dostert [11] proposed an adapted echo model with low-pass behaviours typically observed in practical networks. This model combined multipath propagation, frequency and length-dependence attenuation present in power line networks. The model is given in equation (1) and is characterised by a weighting factor g_i, an attenuation and a delay portion.

$$H_{PLC}(f) = \sum_{i=1}^{N} g_i \cdot e^{-(a_0 + a_1 f^k) d_i} \cdot e^{-j2\pi f \frac{d_i}{v_p}}. \tag{1}$$

In (1), a_0, a_1 and k are attenuation parameters determined from the frequency response magnitude of the complex channel transfer function measured. The path parameters g_i and d_i are obtained from the impulse response information and v_p is the propagation speed of light in the cable.

Noise characteristics in PLC has been extensively studied and reported in [13], [18], [19]. From the literature study, three major noise categories are always encountered in PLC; colored background noise, narrowband noise and impulsive noise [17], [19].

B. The VLC Channel

The VLC channel is the space between the LED and the photodetector (PD). Its transfer function is modelled by LOS and NLOS components [7]. The LOS components is a direct result of the illumination from the LED falling on the photodetector (PD) receiver. However, as a result of obstacles and walls surfaces of the room, a diffused component of the transmitted light is reflected by the walls and obstacles which thereby contributes to the NLOS or diffused component of the channel. Following [6], [7] the generalised VLC channel frequency response can be represented as:

$$H_{VLC}(f) = \sum_{i=1}^{N} \eta_{LOS,i} e^{-j2\pi f \Lambda_{LOS}} + \frac{\eta_{DIFF}}{1 + jf/f_0} e^{-j2\pi f \Lambda_{DIFF}}. \tag{2}$$

In (2) η_{LOS} and η_{DIFF} represent the channel gain for the LOS and NLOS signal, respectively. These are both related to the receiver's surface area and the room properties [3], [7]. Λ_{LOS} and Λ_{DIFF} are signal delays over their respective links and f_0 is the cut-off (3-dB) frequency of the purely diffuse channel.

The LOS and NLOS component for the ith LED chip in (2) above is given by

$$\eta_{LOS,i} = \left[\frac{A_r(m+1)}{2\pi L^2}\right] \cos^m(\Phi_i) \cos(\Psi_i), \tag{3}$$

and

$$\eta_{DIFF} = \frac{A_r \beta}{A_{room}(1-\beta)}, \tag{4}$$

respectively. A_r and A_{room} are the receiver's and room's area respectively with β being the average reflectivity of the room. The distance between the transmitter and the receiver is L with Φ and Ψ being the angle of irradiance and incidence respectively. The variable m is the Lambert index which is given by

$$m = \frac{\ln(2)}{\ln(\cos \phi_{1/2})}, \tag{5}$$

with $\phi_{1/2}$ being the LED's semi-angle of half power.

In a VLC system, two major sources of noise can be identified in VLC: shot and thermal noise. At the receivers, an optoelectrical (light to an electrical signal) conversion is performed. Sources of interference originate from other light sources such as ambient light sources (background solar radiation through windows, incandescent and fluorescent lights radiation) and from the electrical pre-amplifier noise, induced in the PD at the receiver [20]. Shot noise is often dominant in the presence of ambient noise and in their absence, the dominance is thermal noise [21]. Thermal noise ($\sigma^2_{thermal}$) on the other hand is a broadband noise arising from the thermal fluctuations in the electron density within the PD. Shot noise (σ^2_{shot}) in VLC is modelled as white distribution [21]. Taking into account interference at the receiver, the VLC noise can be represented as

$$N_{VLC} = \sigma^2_{shot} + \sigma^2_{thermal} + \gamma^2 P_{isi}, \tag{6}$$

where γ^2 and P_{isi} are the PD responsivity and the power of the inter symbol interference (ISI) respectively.

C. LED Supply

LEDs are semiconductors associated with long-life spans and energy savings. They operate in either forward or reverse-biased modes [6] and need an LED driver to be operated. The LED supply or driver performs two main task:

- Converts the high AC voltage from the mains to a low DC voltage.
- Controls the voltage and current flowing through the LED into a required rated value.

Light emitted by LEDs is proportional to its current supply. Hence, LEDs drivers are either constant-current or constant-voltage in order to operate the LED within a certain current range, which when not maintain, could result to flickering, variation of light output and faster degradation. A recent survey detailing the advances and the structure of various LED drivers can be referred in [22].

LED drivers can be made of simple passive or complex switching components. However they are mostly based on the switched mode power converter topologies [22] which have also been reported to be major source for noise in PLC channels [23].

LEDs switch mode power supply (SMPS) are design to be compact in size, low in power loss, precise in regulating the output and operate at high-frequency switching [22]. Its switching activities will generate different category of noise which are inventoried in [24] and are generally impulsive. In a PLC-VLC environment, the behaviour of the SMPS will affect the noise spectrum in both domains, by attenuating the noise from the PLC channel, generating noise back to the PLC channel or to the VLC channel based on its output current or voltage. Therefore, the LED driver and its design is significant for the PLC-VLC channel modelling and characterisation. Observing the channel noise spectrum at the input and output of an LED driver will provide more insight about its effects on the cascaded PLC-VLC channel.

III. Practical PLC-VLC Noise measurement campaign

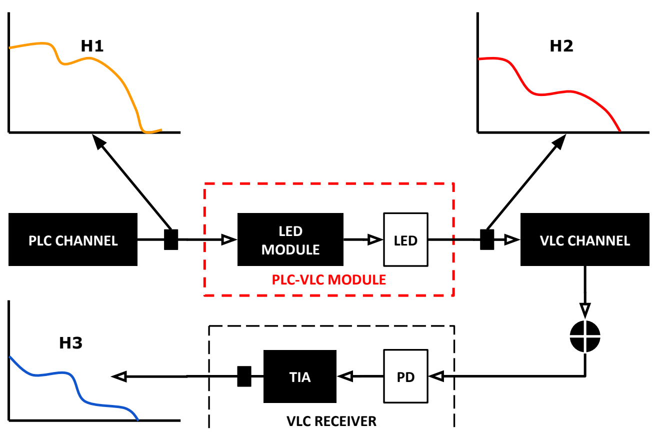


Fig. 2. Experimental measurement block diagram showing the NAS measurement points

The experimental measurements are taken in three locations in order to evaluate and analyze the noise effects of the LED driver on the PLC-VLC channel. These three locations are shown in Fig. 2. In our experiment, we aim at measuring and obtaining the noise amplitude spectrum in a cascade PLC-VLC system. By observing the PLC channel noise spectrum before the LED supply and the one after the LED supply, we are able to spot a frequency varying noise clipping and amplification of the PLC disturbances by the supply. Figs 3 and 4, present measured NAS for two different LED SMPS over a 3 MHz band. From these figures, we can observe a correlation between $H_1(f)$, $H_2(f)$ and $H_3(f)$ from Fig 2.

The correlation between the measured $H_1(f)$ and $H_2(f)$ from Fig. 2, describes the effect of the LED power supply on the system. From Figs. 3 and 4, we can observe that the LED supply either clips and attenuate the noise signal present

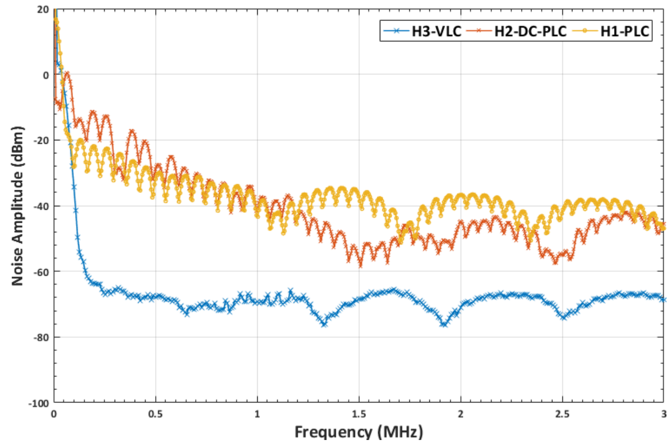


Fig. 3. Measured NAS of a noisy LED power supply characterised by DC ripples and switching noise

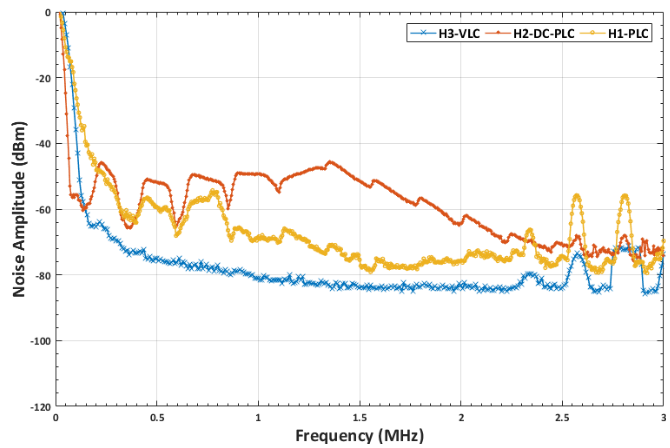


Fig. 4. Measured NAS of a smoother LED output power supply

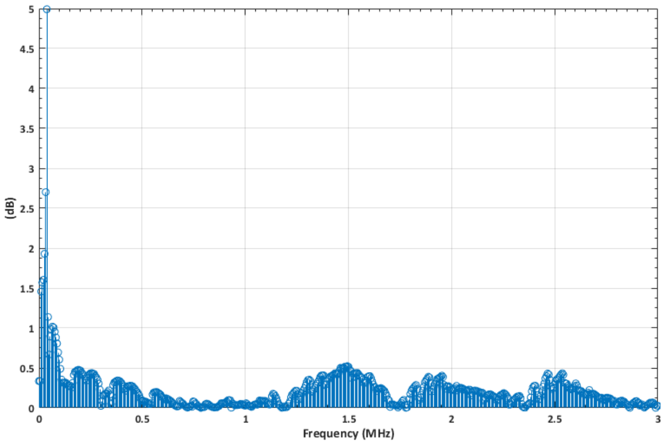
over the PLC channel or amplifies it by a factor $\delta(f)$ which is define as:

$$\delta(f) = \left| \frac{H_1(f) - H_2(f)}{H_1(f)} \right|. \tag{7}$$

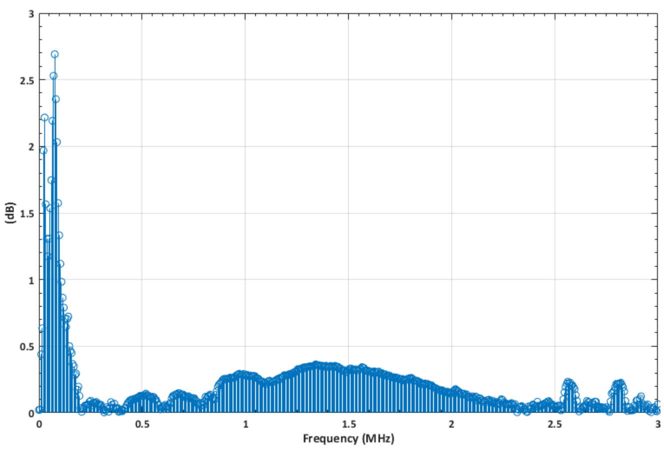
In Fig. 5, we can observe a plot of $\delta(f)$ as a function of frequency, for two different LED supply used in our experiment. For a $\delta(f) = 1$ it implies the driver is an all-pass filter, $0 < \delta(f) < 1$ the driver amplifies $H_1(f)$ and for $\delta(f) \geq 1$ the driver attenuates $H_1(f)$. Our parameter $\delta(f)$ is therefore added and considered in our proposed model.

IV. Simplistic PLC-VLC Channel Model

The proposed model integrates two independent communication channels in cascade. This will result in the superposition of their respective transfer function and noise components. However, a direct convolution of both channel is not closely related to the previous practical observation. Furthermore, a direct convolution of both transfer function will result in the PLC channel just being shifted-down, and therefore further assuming no PLC noise crosses through to the VLC domain.



(a)



(b)

Fig. 5. $\delta(f)$ for the two LED power supply used

As we saw in the previous experiment, this is not totally correct and the LED supply does act on the system. The LED supply which connects the PLC signal to the VLC domain has a non-negligible effect on the overall cascaded channel. It can be said to act as a transfer function as well. In our model, we include the factor $\delta(f)$ introduced above in the convolution. We can therefore summarise the overall PLC-VLC channel as:

$$H_{PV}(f) = [\delta(f) \times H_1(f)] \times H_3(f), \tag{8}$$

where $H_1(f)$ and $H_3(f)$ corresponds to the PLC and VLC transfer function respectively.

$$H_{PV}(f) = \delta(f) \times [H_1(f) \times H_3(f)], \tag{9}$$

$$H_{PV}(f) = \delta(f) \times H_{1,3}(f). \tag{10}$$

In (10), $H_{1,3}(f)$ is the convolution of the two impulse responses, which, in the frequency domain is the multiplication of the transfer functions. Using the PLC transfer function $H_{PLC}(f)$ from 1 and the VLC transfer functions $H_{VLC}(f)$ from 2, we can obtain (11):

$$\begin{aligned} H_{1,3}(f) &= H_{PLC}(f) \times H_{VLC}(f) \\ &= \left[\sum_{i=0}^{L_s-1} g_i \cdot e^{-(a_0+a_1 f^k)d_i} \cdot e^{-j2\pi f \frac{d_i}{v_p}}\right] \\ &\quad \left[\eta_{LOS} e^{-j2\pi f \Lambda_{LOS}} + \frac{\eta_{DIFF}}{1+jf/f_0} e^{-j2\pi f \Lambda_{DIFF}}\right]. \end{aligned} \tag{11}$$

With some expansion, this gives us

$$\begin{aligned} H_{1,3}(f) &= \sum_{i=0}^{L_s-1} g_i \cdot e^{-(a_0+a_1 f^k)d_i} \eta_{LOS} e^{-j2\pi f\left(\frac{d_i}{v_p}+\Lambda_{LOS}\right)} \\ &\quad + \frac{\eta_{DIFF}}{1+jf/f_0} e^{-j2\pi f\left(\frac{d_i}{v_p}+\Lambda_{DIFF}\right)}. \end{aligned} \tag{12}$$

We can use the fact that $\frac{d_i}{v_p} \gg \Lambda_{LOS}$ and $\frac{d_i}{v_p} \gg \Lambda_{DIFF}$ and with further simplifications we can therefore get that $H_{1,3}$ is given by (13)

$$\begin{aligned} H_{1,3}(f) = \sum_{i=0}^{L_s-1} \Bigg[g_i \cdot e^{-(a_0+a_1 f^k)d_i} \Bigg(\eta_{LOS} \\ + \frac{\eta_{DIFF}}{1+jf/f_0} \Bigg) e^{-j2\pi f\left(\frac{d_i}{v_p}\right)} \Bigg]. \end{aligned} \tag{13}$$

The final PLC-VLC frequency response model is obtained by substituting (13) in (10), which is therefore given by (14) :

$$\begin{aligned} H_{PV}(f) = \delta(f) \cdot \sum_{i=0}^{L_s-1} \Bigg[g_i \cdot e^{-(a_0+a_1 f^k)d_i} \Bigg(\eta_{LOS} \\ + \frac{\eta_{DIFF}}{1+jf/f_0} \Bigg) e^{-j2\pi f\left(\frac{d_i}{v_p}\right)} \Bigg]. \end{aligned} \tag{14}$$

From (14), we can observe that, the PLC-VLC channel is dependent on significant parameters from both PLC and VLC channels. Parameters such as the number of PLC taps, the VLC LOS and NLOS path gain together with the LED supply parameter $\delta(f)$, will all have and effect on the PLC-VLC channel frequency response.

This derived model, is simulated and the results are presented in the following section. In our simulation, we highlight the effects of the above mention different parameters on the PLC-VLC channel frequency response.

V. Results and Discussion

In this section, we report and analyse the simulation results of our proposed model. Table I, provides the various relevant parameters used in our simulation. This table summarises an evaluates a bad PLC-network environment with 6 taps over a 10 MHz bandwidth. The VLC environment is characterised by a room of about 25 m^2 in area, the VLC receiver with 3 cm^2 effective surface area at a distance of about 3 m away from the the LED transmitter. Other environment parameters are shown in Table I.

In Fig. 6, we show the PLC-VLC channel frequency response resulting from the parameters given in Table I. The

TABLE I
RELEVANT PARAMETERS

PLC-CHANNEL	
a_0	0
a_1	1.1×10^{-8}
k	1
Bandwidth	10MHz
g	[-0.0039 0.0156 -0.034 0.0715 -0.122 0.076]
d	[78 126 191 256 306 330]
VLC-CHANNEL	
A_{room}	25 m^2
A_r	3 cm^2
L	3 m
f_0	8.3 MHz
Φ	70
Ψ	60
β	0.8
η_{DIFF}	5.3×10^{-6}
η_{LOS}	1.3×10^{-6}

figure shows both the PLC channel and the resulting PLC-VLC channel. The results shows that the PLC-VLC channel is characterised by notches which varies throughout the entire frequency band. We can also observe the effect of the VLC channel which attenuates the PLC channel frequency response. The PLC-VLC channel also turns to mimic and approximate the low-pass frequency characteristics of the PLC channel.

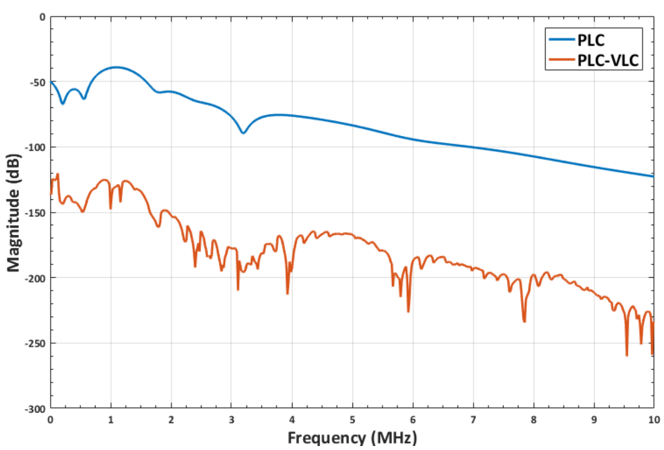


Fig. 6. Simulation result of a 6 PLC Taps network with the resulting PLC-VLC channel

We further vary the PLC channel parameters to emulate different PLC environment and frequency response. In Figs. 7 and 8 we present two other PLC network simulated and the resulting PLC-VLC channel obtained from our model. Fig. 7 shows how a good PLC channel response can still produce a rough PLC-VLC channel as a result of the various switching activities present in the LED supply. While in Fig. 8, the effect of an increase in number of PLC taps in the network is presented.

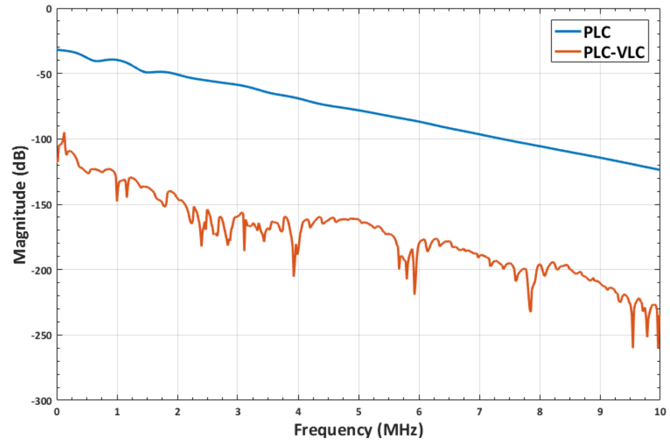


Fig. 7. Simulation result of a 5 PLC Taps network with the resulting PLC-VLC channel

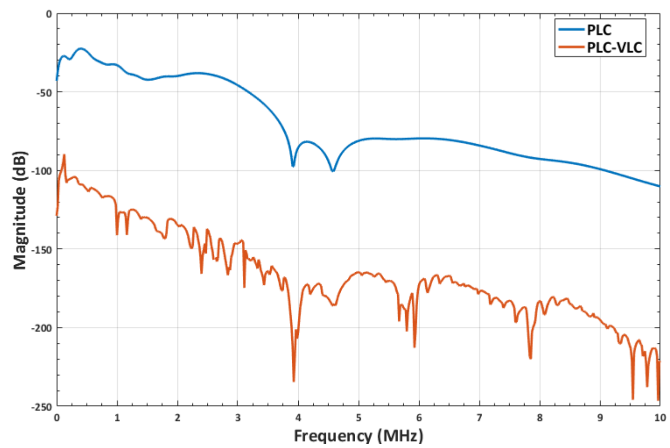


Fig. 8. Simulation result of a 12 PLC Taps network with the resulting PLC-VLC channel

In Fig. 9, we show the effect of the VLC channel parameters on the PLC-VLC channel. The K-factor is a ratio between the VLC channel LOS gain over the NLOS gain. By varying the K-factor, we are able to emulate the VLC environment in terms of how much of the direct link or diffuse link is captured by our VLC receiver.

In Fig. 10, we superimpose in a single plot multiple PLC channel paths applied through our model. The simulation was done by using the same VLC parameters given in Table I, and the PLC parameters used where: $a_0 = 0$; $a_1 = 7.8 \times 10^{-10}$, Bandwidth = 30 MHz, g and d varying randomly between {-0.065, 0.065} and {90 m, 300 m} respectively. The figure shows the resultant PLC-VLC channels paths obtained from our model.

VI. CONCLUSION

In this paper, we proposed a channel model for hybrid PLC-VLC cascaded systems. The model takes into consideration effects of the LED power supply which contributes significantly

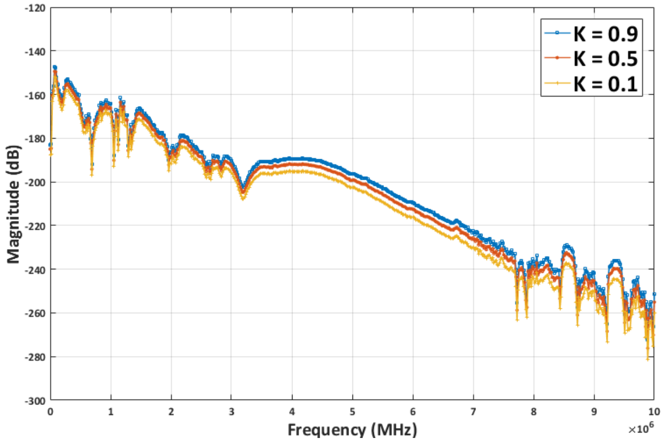


Fig. 9. Resultant PLC-VLC channel with varying K-factor

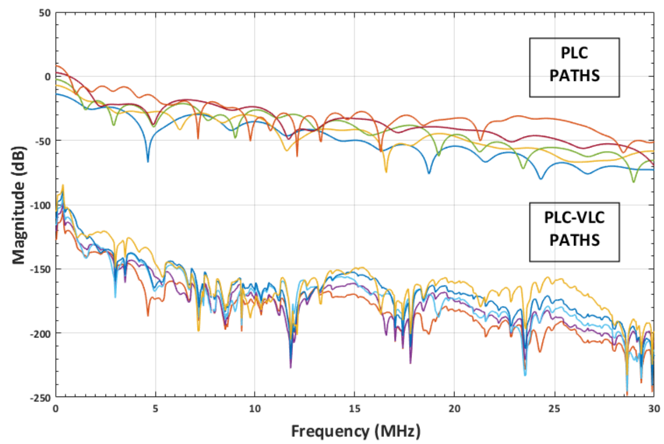


Fig. 10. Varying PLC channel paths and Taps with their resultant PLC-VLC channel paths

on the overall hybrid channel. In our work, we practically measure the noise amplitude spectrum of both PLC and VLC channels, and observed the effect of the LED supply. We then define relevant parameters used in simulating the proposed channel model. In our result, we subject different and realistic, referenced PLC channels to our model and obtain resultant PLC-VLC channels.

Currently, more measurements are being done so as to obtain extra informations on the behaviour and effect of the LED supply on the overall channel characterisation.

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