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Cascaded PLC-VLC Channel: An Indoor Measurements Campaign

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ABSTRACT Recently, power line communication (PLC) technology has been associated with the emerging visible light communication (VLC) technology. PLC technology is matured and has gained from tremendous research contributions over the past years. VLC technology, relatively new, utilizes light emitting diodes (LED) to transmit information through the visible light portion of the electromagnetic spectrum. Their hybrid systems are attractive in their ubiquitousness for providing power delivery, illumination, and data transmission. Furthermore, such a hybrid system is cost effective due to its infrastructure already being used for other means. In this paper, we report on channel frequency measurement of a hybrid cascaded PLC-VLC channel. These measurements performed in a laboratory environment demonstrate the influence of power line activities and the LED supply on the hybrid PLC-VLC channel response. Based on previous models and the observed behaviors, we present simulation results of a PLC-VLC channel model. In our results obtained, the effect of the LED supply on both channels is emphasized and also considered in the proposed model. Finally, this paper provides an overall characterization, model and spectral analysis for hybrid PLC-VLC channels, which is critical for effective promotion and mass production of hybrid PLC-VLC systems.

INDEX TERMS Cascaded channel, Channel model, Channel measurement, Power line communication, Visible light communication, PLC-VLC systems, PLC-VLC Channel.

I. INTRODUCTION

HYBRID power line communication (PLC) and visible light communication (VLC) systems are emerging and prominent communication technologies. They use ubiquitous infrastructures which make provision for data transmission, power delivery and illumination through the power line cables and light emitting diodes (LED) luminaries. In PLC-VLC cascaded systems, PLC technology is used as a backbone for the communication infrastructure and VLC technology makes provision of transforming a PLC signal into a wireless optical one [1]. The enormous research progress and achievements made in solid state lighting points out the advantage of using LEDs as a primary source of illumination. LEDs are characterized by their high efficiency and brightness, together with long life span, energy saving and low cost. In addition to all these properties, LEDs ability to have their current intensities easily modulated as compared to other light bulb sources [2], justifies the emerging of VLC technology.

On the one hand, research on PLC technology is relatively mature and the PLC channel has greatly and extensively been characterized and studied, with significant contributions [3]–[8] provided by the research communities. Noise in PLC is mainly categorized as background, narrow-band, and impulsive noise. Narrow-band interference result from the frequency sharing between PLC technology and radio amateurs. Impulsive noise, categorized as periodic and aperiodic, is mainly generated by both human activities and electric appliances connected to the lines, and background noise groups the rest of noise generated over the PLC channel. Most of the appliances (computers, flat screens, monitors, TVs, printers, and many others appliances) are provided with a switch mode power supply (SMPS); thus, appliances in their operation, produce a lot of noises that contributes to the characteristics and disturbances of the PLC channel. VLC technology on the other hand, is less mature when compared to PLC technology. It is however described as being a short-distance optical wireless communication [2], and will inherit from most of the optical communication characteristics. VLC systems are based on the fast switching LED's capability and transmit data by modulating the light intensity [1], [9]. The information is conveyed through the visible portion of the electromagnetic spectrum, which is in the range 380 to 780

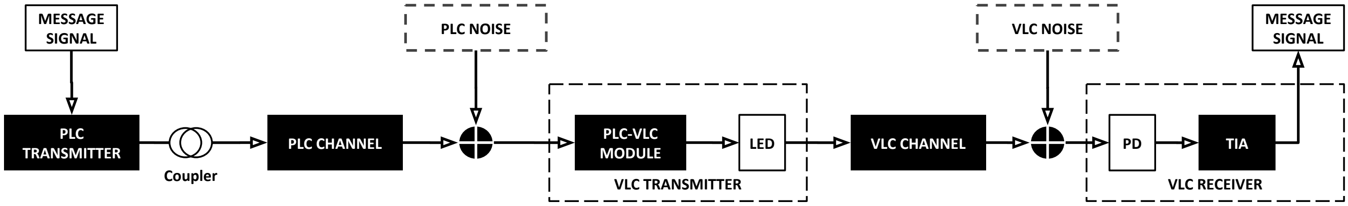


FIGURE 1: Generalized functional block diagram for an integrated PLC-VLC system.

nm. In addition to the aforementioned characteristics, VLC requires a real and unipolar signal to achieve transmission. VLC is further considered as a prominent, radiation free, and could be an alternative solution to the crowded radio spectrum. VLC has been attractive to the current research community and is tied to numerous applications such as indoor localization [10], mobile connectivity [11], hospitals or health care [12], [13] related applications and many other.

The very first hybrid PLC-VLC system was presented by Komine et. *al* in [14]. The test-bed was demonstrated using a single carrier binary phase shift keying (SC-BPSK) over the power line, which was converted into an unipolar signal compatible with visible light. Since then, many research findings are provided in hybrid PLC-VLC systems. The authors in [15] discussed and proposed various integration scenarios for PLC and VLC, intended towards more of a PLC audience. They distinguished two ways for combining both PLC and VLC technology; decode-and-forward (DF) and amplify-and-forward (AF). Furthermore, different possible scenarios are also discussed. In [16], a broadcasting system based on cascaded PLC-VLC is demonstrated, in [17] Quadrature phase shift keying combined with orthogonal frequency division multiplexing (QPSK-OFDM) in cascaded PLC-VLC is presented and recent work investigate multi-user [18] and multi-service transmissions [19].

So far, relatively little attention has been given to cascaded PLC-VLC channel characterization Recently [20] proposed a non-parametric estimation assuming a linear PLC-VLC channel model and [21], [22] also give a study of the integrated channels. Still few questions remain unanswered, mainly with regards to the noise behavior and its influence on both channels. In this paper, we proposed a spectral analysis, an investigation, and, a measurement campaign of the PLC-VLC channel, which leads to a channel model for PLC-VLC systems. Such a system is modeled and proposed in Fig. 1. It shows a generalized block diagram for integrated PLC-VLC system. The signal is sent through a PLC transmitter, received at the end by a VLC receiver and is affected by the channel and noise present in both PLC and VLC channels. The PLC environment is highly frequency selective and time variant with interference and noise issues making it a harsh environment for communication. This investigation is performed through a series of channel noise amplitude spectrum (NAS) measurements and simulated derived channel response, which both seeks answers to few questions such as

- What is the influence of the PLC channel on the VLC channel? and vice-versa?
- What is the influence of both channels on the cascaded PLC-VLC channels?

The main contributions of this paper are therefore summarized as follows

1) Spectral measurement and analysis of the hybrid PLC-VLC channel.
2) Simulation and modeling of the hybrid PLC-VLC channel.

The remainder of this paper primarily presents in section II, a quick review of PLC and VLC channels, their models and the noise scenario. In Section III we elaborate on the experimental measurements performed and this is followed by its analysis and results in Section IV. Section V gives the proposed model and its simulation results. Finally concluding remarks are given in Section VI.

II. PLC AND VLC CHANNELS AND NOISE SCENARIOS

A. THE PLC CHANNEL

The PLC channel is a harsh environment and very difficult to model as a result of 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 [23].

Channel modeling in PLC can be done by top-down [24], [25] or bottom-up [8] approaches also known as time domain and frequency domain-based modeling [26] respectively. The bottom-up approach treats the PLC channel as a black-box and produces an analysis of its response by fitting results from measurements. This approach exploits transmission line theory in order to produce the PLC channel transfer function. Details about power line channel modeling was done using this method can be found in [5], [8], [26].

The top-down approach done in the time domain describes the power line channel being affected by multi-path effects. This effect is as a result of multiple branches and mismatches of impedance present in the power line channel. The echo-based channel model with N different paths has the following impulse response [25], [26]:

$$h_{plc}(t) = \sum_{i=0}^{N-1} k_i \delta(t - \tau_i), \quad (1)$$

where the coefficients k_i and τ_i are respectively the attenuation and paths echo delays. Zimmermann and Dostert [25] proposed an adapted echo model with low-pass behaviors typically observed in practical networks. This model combined multi-path propagation, frequency and length-dependence attenuation present in power line networks. The model is given in equation (2) and is characterized by a weighting factor g_i, an attenuation ($e^{-(a_0+a_1f^k)d_i}$) and a delay ($e^{-j2\pi f\frac{d_i}{v_p}}$) portion [25].

$$H_{plc}(f) = \sum_{i=1}^{N} g_i \cdot e^{-(a_0+a_1f^k)d_i} \cdot e^{-j2\pi f\frac{d_i}{v_p}}. \quad (2)$$

In (2), 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.

Power line noise has been extensively studied and reported in [3], [4], [26]. Colored background noise is characterized by a low power spectral density (PSD) which increases at low frequencies. It originates from several common household appliances such as computers and fridges. Their PSD often varies in minutes or hours. Background noise is often modeled as [27]

$$A(f) = A_\infty + A_0e^{\frac{-f}{f_0}}, \quad (3)$$

where A_∞ is the power density as $f \rightarrow \infty$, A_0 is the difference between $A(\infty)$ and $A(0)$. Narrow-band noise is composed of modulated sinusoids amplitude. This originates from the fact that broadcasting radio stations share the frequency band with BBPLC systems. Narrow-band noise is often modeled as a sum of multiple sinusoids [26].

$$n_{NB}(t) = \sum_{i=1}^{N} A_i(t)\sin(2\pi f_i t + \theta_i), \quad (4)$$

where N is the number of carrier waves with different amplitudes A_i, frequencies f_i and phases θ_i. On the other hand, impulsive noise is short in duration (typically few micro-seconds to milli-seconds), large amplitudes and abrupt disturbance in PLC channels. It is further classified as periodic synchronous, periodic asynchronous and asynchronous aperiodic impulsive noise. These impulses are often large in amplitudes, short in durations and occur abruptly [26]. The periodic synchronous noise is often generated by rectifiers such as those found in DC power supplies and by triac or thyristor related devices such as light dimmers [4]. Their impulses occur at frequency multiples of the mains' frequency while periodic asynchronous repetition rates are much higher (50-200 kHz) and results from extended switching in SMPS of household appliances.

B. THE VLC CHANNEL

The VLC channel is the space between the LED and the photodetector (PD). Its transfer function is modeled by a line-of-sight (LOS) and a non-line-of-sight (NLOS) components [28]. The LOS components is a direct result of the illumination from the LED falling on the 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 [2], [28], the generalized VLC channel frequency response can be represented as:

$$H_{vlc}(f) = \sum_{i=1}^{N} \eta_{LOS,i}e^{-j2\pi f\Lambda_{LOS}} + \frac{\eta_{DIFF}}{1+jf/f_0}e^{-j2\pi f\Lambda_{DIFF}}. \quad (5)$$

In (5) 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 [16], [28]. 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 i^{th} LED chip in (5) is given by

$$\eta_{LOS,i} = \left[\frac{A_r(m+1)}{2\pi L^2}\right]\cos^m(\Phi_i)\cos(\Psi_i), \quad (6)$$

and

$$\eta_{DIFF} = \frac{A_r\beta}{A_{room}(1-\beta)}, \quad (7)$$

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 d with Φ and Ψ being the angle of irradiance and incidence respectively. The variable m is the Lambertian index which is given by

$$m = \frac{\ln(2)}{\ln(\cos\phi_{1/2})}, \quad (8)$$

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: shot and thermal noise. At the receivers, an opto-electrical (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 [29]. Shot noise is often dominant in the presence of ambient noise and in their absence, the dominance is thermal noise [30]. 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 in VLC characterized by its variance, σ^2_{shot}, is modeled as white distribution [30]. Taking into account interference at the receiver, the VLC noise variance can be represented as

$$n(t) = \sigma^2_{shot} + \sigma^2_{thermal} + \gamma^2 P_{isi}, \tag{9}$$

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

C. THE LED SWITCH MODE POWER SUPPLY

All power supplies provided with SMPS produce the same type of noises. Scanning the switch mode power supply, we inventory many categories of noises as presented in [5]:

- The impulsive noise is present in SMPS; it is due to some random transient phenomenon in the switches used in the power supply. For example the first peak of Ground Bounce is an impulse noise;
- Crosstalk noise is present in SMPS; this noise is a consequence of the EMI phenomenon inside the switch;
- Thermal noise, due to the thermal agitation of electrons in motion in the SMPS circuit;
- Shot noise; arises from electronic components like diodes and transistors;
- Generation - recombination noise is present in the power supply;
- Inter-modulation noise occurs when two signal at different frequencies are mixed in the same medium; noises are produced at harmonic frequencies, at the sum, the difference and the multiple of the two original frequencies.
- Flicker noise is a low frequency noise. This noise is reduced when the switching is done at high frequencies;
- Delta-I noise: Also called "Ground Bounce", "Switching noise", "Simultaneous switching noise" (SSN), "Simultaneous switching output noise" (SSO), this noise is caused by the switching, it refers to the voltage fluctuation between power and ground conduction, caused by sudden current surge. The noise is composed by one impulse accompanied by many oscillations. The first peak which is an impulse noise is one of the most dangerous noises transmitted in the PLC channel. Part of SSN is transferred to the PLC through the EMI filter and became the periodic impulse noise.

D. THE PLC-VLC CHANNEL

Being connected to one another, both channels will have an effect on each other and all the previous elaborated noise of each channel can be superimposed in the PLC-VLC channel. In Fig. 2 we illustrate the possible noise scenario in a PLC-VLC integration. In such a hybrid systems, the communication is done through a "PLC to VLC" module [16], [31] which will either DF or AF the transmitted signal from the PLC channel [15]. In either of the methods, a coupler and a LED supply are always equipped as part of the module. However, the channel is only considered linear or cascaded with the AF method. The LED supply is often equipped with SMPS; major background noise sources in the PLC channel. The switching activities in these supplies are fed back into the PLC network where they contribute to its periodic and aperiodic impulsive noise. The topology and components making up the supply will affect the noise propagation across both PLC and VLC channels. Besides the propagated supply noise which could reach the VLC receiver, it will also generate its own noise as a result of ambient light, which explains the direction from and into the receiver. Noise behavior of the LED supply can be mitigated by EMI filters which are often used in computer's SMPS, but often omitted in LED supplies as a result of cost and size.

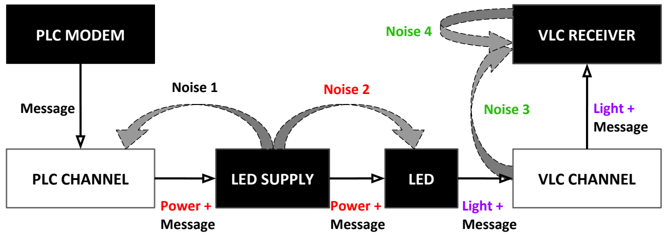
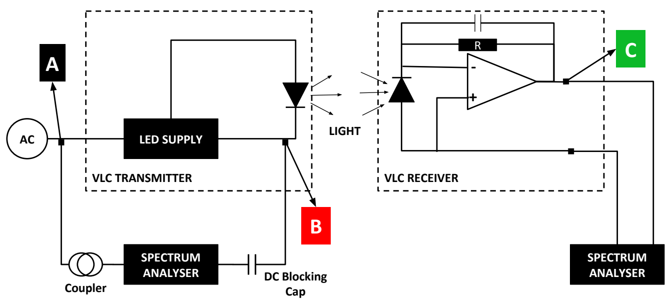


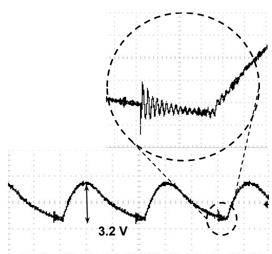
FIGURE 2: PLC-VLC channel noise and disturbances.

III. EXPERIMENTAL MEASUREMENT CAMPAIGN

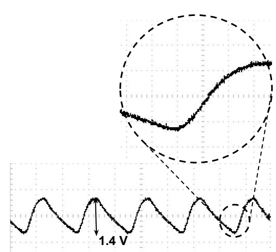
The schematic experimental setup used to perform a frequency-domain measurement is shown in Fig. 3(a). The Center for Telecommunications laboratory (B2 LAB 210, faculty of Engineering, University of Johannesburg) was used to conduct the experiment. In our experiment, in order to show the effects a LED supply, may have on both channels. We used three different drivers to power our LED, namely Supply 1, 2 and 3. A commercially rated 3 W, 300 mA power



(a) Measurement set-up used to analyze the PLC-VLC noise amplitude spectrum. The measurement points are highlighted and the principle of the TIA is shown.

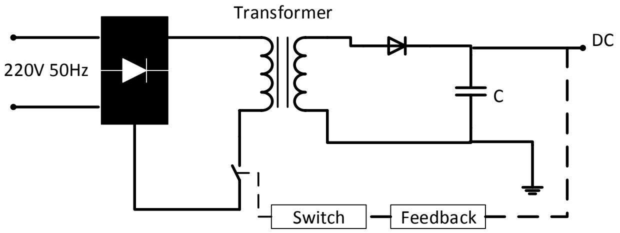


(b) Supply 1

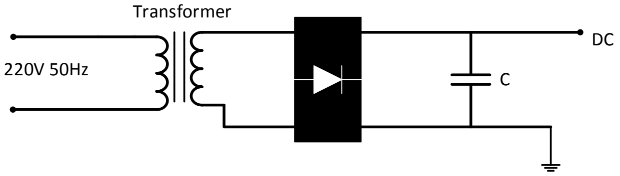


(c) Supply 2

FIGURE 3: Voltage output characteristic of the SMPS used.



(a) Supply 1 and 3



(b) Supply 2

FIGURE 4: Topology of the different supplies showing topologies and principles of the three LED supplies used in the experiments.

LED is driven using a LED supply connected to the power line. Its light is directed on the surface of a photo detector (PD) powered by a 5 V supply. The LED is placed at 30 cm from the PD. The channel noise activities are observed using the spectrum analyzer. Three locations are evaluated in order to analyze the noise effects on the PLC-VLC channel: *(i)* the LED's supply input (point A on Fig. 3(a)), *(ii)* the LED supply's output (point B on Fig. 3(a)) and at *(iii)* PD's output (point C on Fig. 3(a)). The signal measurement at point "A" is performed via a coupling circuit which stops the low frequency high power AC signal. At "B", a DC-blocking capacitor is inserted to block the DC-signal component from influencing the results. A trans-impedance amplifier (TIA) is integrated into the PD and it amplifies the current converted by the PD into a voltage.

Supply 1 is the original SMPS of the LED lamp. It provides the LED with a maximum rated current of 0.3 A at 10 V. However, this supply was not providing a clean DC supply. It is characterized by high voltage ripples around 3.2 V peak-peak with some switching noise as observed in its time domain voltage measurement shown in Fig. 3(b). Supply 2 is a DC supply consisting of a step-down transformer (220V-12V), a bridge rectifier and a power resistor in series with the LED. The supply has lower ripple around 1.4 V peak-peak as shown in Fig. 3(c) however, provided a lower luminosity than supply A. Supply 2 is purely composed of passive components unlike the active ones in Supply 1 which employed switching components, see Figs. 4(b) and 4(a). The last supply used, Supply 3, was a very efficient SMPS without DC output ripples. It was also characterized by the high luminosity it supplies to the LED.

IV. CHANNEL NOISE AMPLITUDE SPECTRUM

In this section we present and discuss the results of our measurements. Figs. 5, 6 and 7 show measurement results obtained on power supplies 1, 2 and 3, respectively. These measurement are performed over three different days, at different time slots daylight and are performed over a broad range of frequencies from 0 to 5 MHz. This range is divided into three Sub-bands that are:

- **Sub-band 1**: This corresponds to CENELEC A, B, C and FCC band 1 frequency range from 0 to 148.5 kHz.
- **Sub-band 2**: This covers the frequency range from 148.5 kHz to 500 kHz and represents the second FCC frequency band. Sub-band 1 and 2 are included in IEEE 1901.2 standard, allocated for low frequency (less than 500 kHz) NBPLC for smart grid applications.
- **Sub-band 3**: This sub-band is a BBPLC and it ranges between 500 kHz and 5 MHz. It also covers part of the IEEE 1901.1 and ITU frequency bands.

For all these frequency bands, we observe significant behaviors of the PLC-VLC combined channel, which are created by the LED power supply. Figs. 5, 6 and 7 group results corresponding to the three subsections presented above. They are identified by (a), (b) and (c), and, each of them shows three PLC-VLC cascaded channels transfer functions named A, B and C over the figures and corresponds to measurement over point A, B and C showed in Fig. 3(a), respectively. In the range between 0 and 500 kHz (0 to 148.5 kHz + 148.5 kHz to 500 kHz), Supply 1 transfers from A to B all noise from the power line channel. This is shown in Figs. 5(a) and 5(b), where B mimics A. On the contrary, in Figs. 6 and 7, this is not the case. In Figs. 6(a) and 6(b), the spectrum shows a noise totally attenuated by the supply and its shape mimics the average of its PLC noise represented by point A on the figures. The spectrum presented in Figs. 7(a) and 7(b) show that the PLC narrow-band noise does not cross the LED supply, which is made of a low frequency transformer. This is materialized by spectrums A and B in Figs. 7(a) and 7(b) that do not follow each other.

Considering the range between 500 kHz and 5 MHz, Supply 1 transfer all noise from the PLC channel to the VLC channel. This is shown in Fig. 5(c), where C mimics A and B. This is similar for supplies 2 and 3. This situation strengthens the theory that at certain high frequencies, power semiconductors may become pure conductors [32].

Considering the measurement results performed on points A and B for the three power supplies, it can be concluded that the LED supply clips and attenuate the noise signal present over the PLC channel. This is shown in Figs. 5(a), 5(b), 5(c); and Fig. 7(c). The attenuation coefficient here depends on the frequency of the noise signal and this reinforces the model presented in [17] showing that the message detected over the PLC channel in an AF scenario undergoes both effects of the PLC and VLC noise and the transfer function of the combined channels.

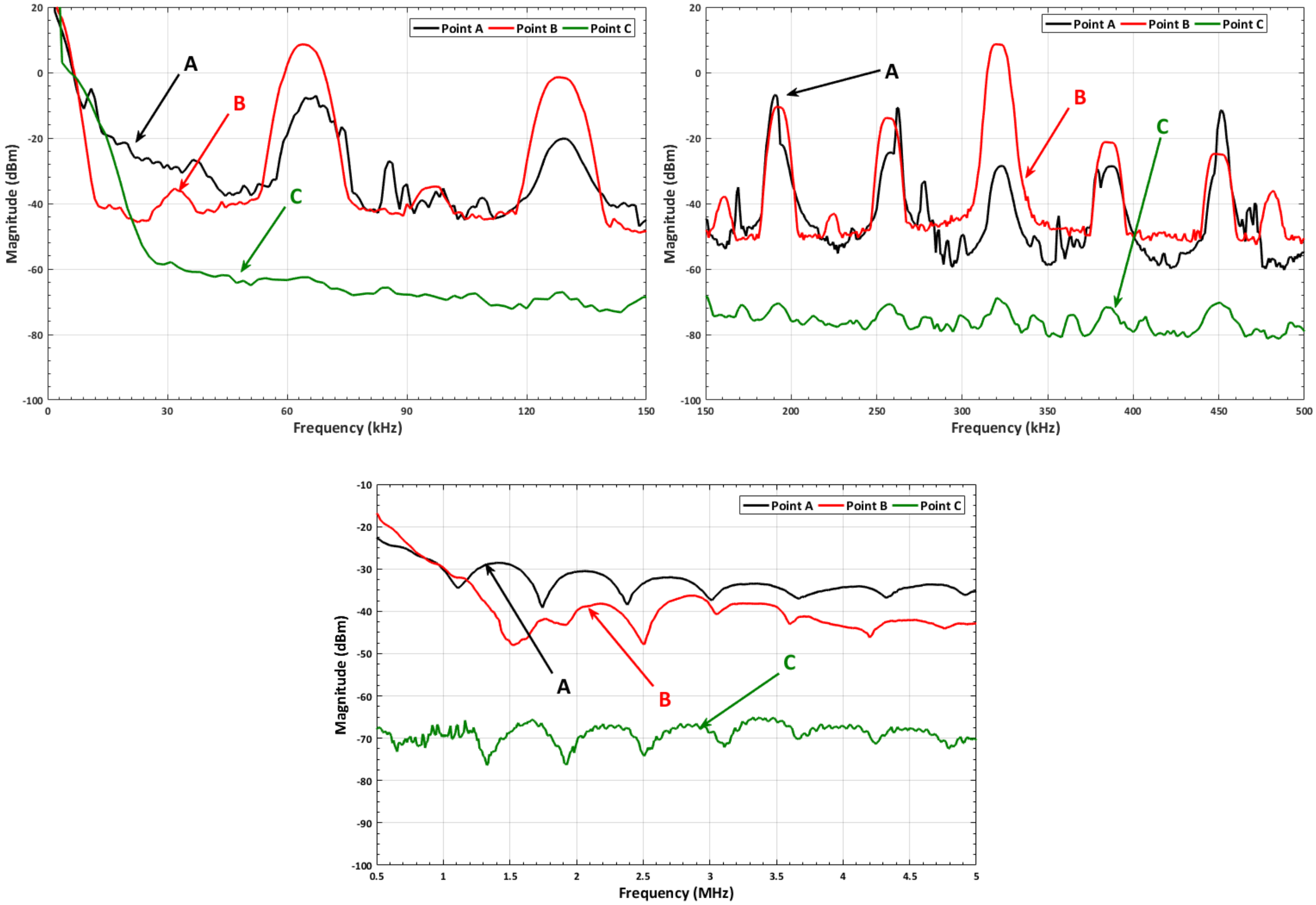


FIGURE 5: Supply 1 - NAS measurement.

V. PLC-VLC CHANNEL MODEL

A. PROPOSED MODEL

In our proposed model we put PLC and VLC communication channels in cascade. This therefore superimposes their respective transfer function and noise components. However, from the presented measurement campaign in Section IV, direct convolution of both channel is not a true representation of the practical measurements. In addition to that, 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. 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 in [21]. $\delta(f)$ is a correlation of the measured NAS at the input and output of the PLC-VLC module, which either clips and attenuate or amplifies the noise signal present over the PLC channel. We can therefore summaries the overall PLC-VLC channel as:

$$H_{pv}(f) = [\delta(f) * H_1(f)] * H_3(f), \tag{10}$$

where H_1 and H_3 corresponds to the PLC and VLC transfer function respectively.

$$H_{pv}(f) = \delta(f) * H_{1,3}(f). \tag{11}$$

In (11), $H_{1,3}$ 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 (2) and the VLC transfer functions $H_{vlc}(f)$ from (5), we can obtain (12):

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

With some expansion, this gives us (13)

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

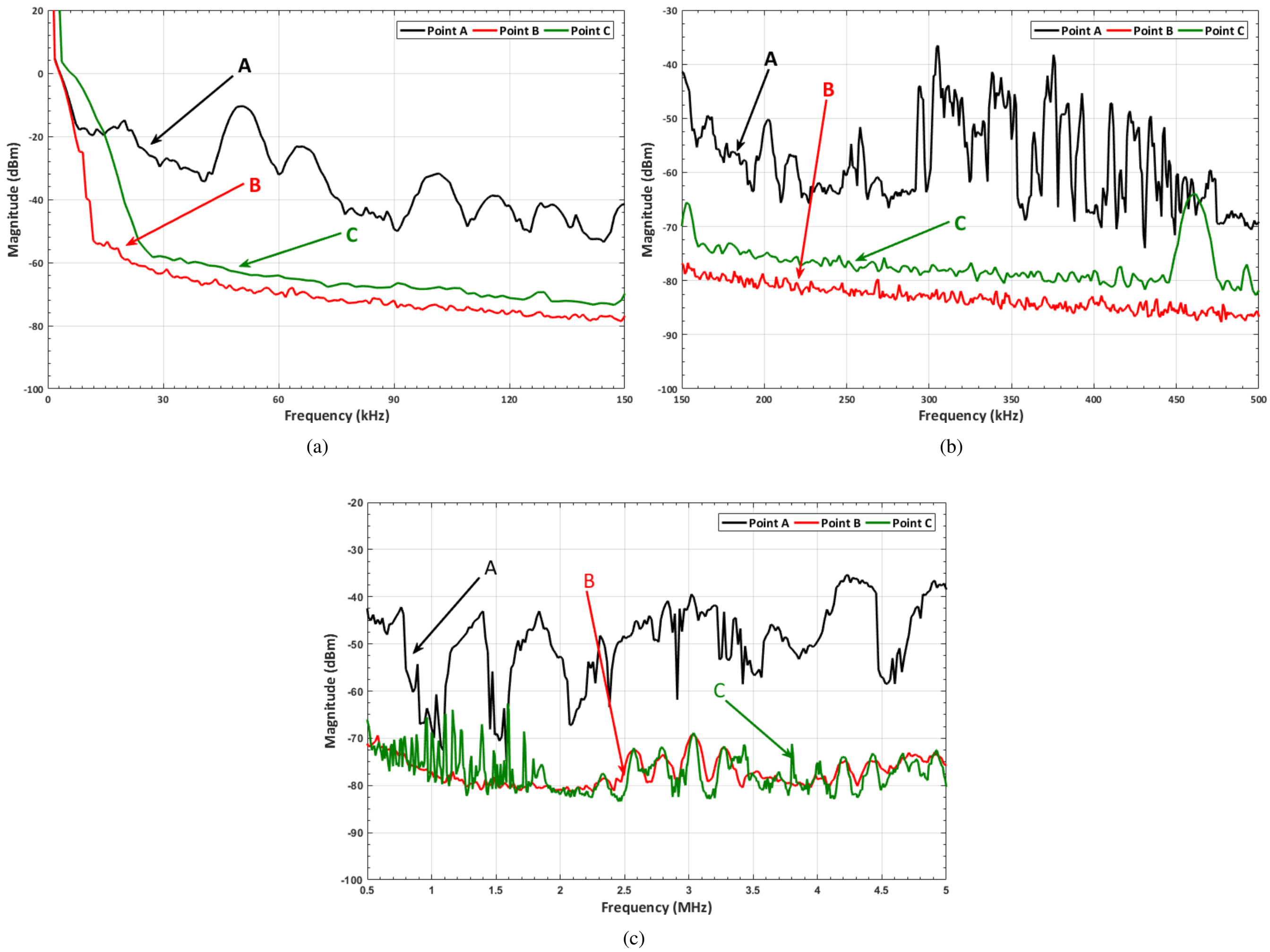


FIGURE 6: Supply 2 - NAS measurement.

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 (14).

$$H_{1,3}(f) = \sum_{i=0}^{L_s-1} \Big[g_i \cdot e^{-(a_0 + a_1 f^k) d_i} \Big(\eta_{LOS} + \frac{\eta_{DIFF}}{1 + jf/f_0} \Big) e^{-j2\pi f \left(\frac{d_i}{v_p}\right)} \Big]. \tag{14}$$

The final PLC-VLC frequency response model is obtained by substituting (14) in (11), which is therefore given by (15).

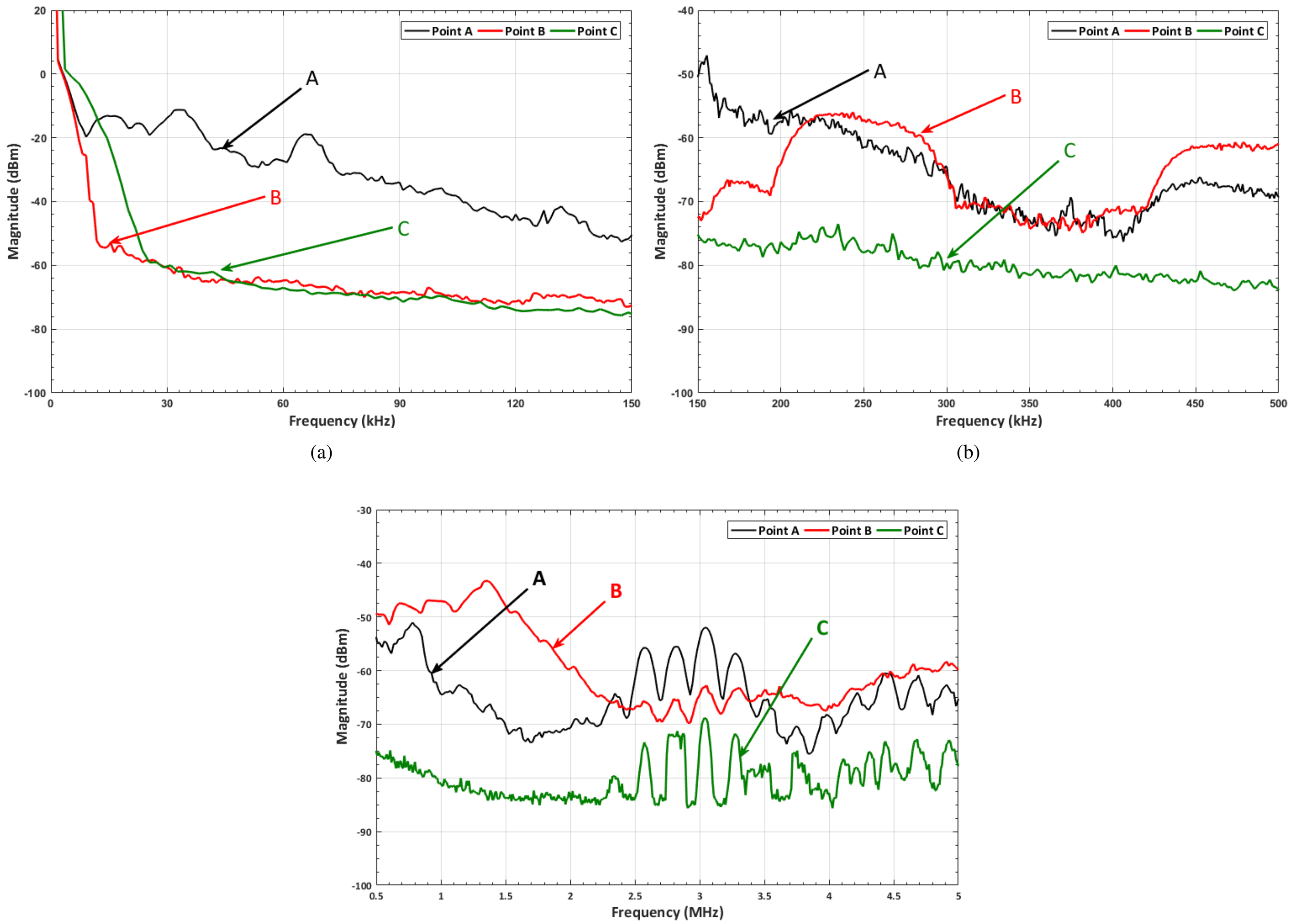
$$H_{pv}(f) = \delta(f) \cdot \sum_{i=0}^{L_s-1} \Big[g_i \cdot e^{-(a_0 + a_1 f^k) d_i} \Big(\eta_{LOS} + \frac{\eta_{DIFF}}{1 + jf/f_0} \Big) e^{-j2\pi f \left(\frac{d_i}{v_p}\right)} \Big]. \tag{15}$$

From (15), we can observe that, the PLC-VLC channel primarily varies with frequency, and 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 δ, 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.

B. PROPOSED MODEL SIMULATION RESULTS

In this section, we report and analyze the simulation results of our proposed model. Table 1, provides the various relevant parameters used in our simulation. This table summarizes an evaluates a bad PLC-network environment with 6 taps over a 10 MHz bandwidth. The VLC environment is characterized 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 the table.

In Fig. 8(a), we show the PLC-VLC channel frequency response resulting from the parameters given in Table 1. The figure shows both the PLC channel and the resulting PLC-



(a) (b) (c)

FIGURE 7: Supply 3, NAS measurement.

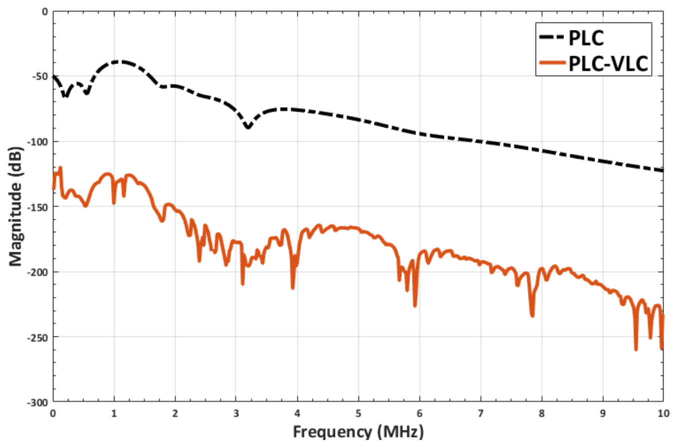
VLC channel. The results shows that the PLC-VLC channel is characterized by notches which varies throughout the entire frequency band. We can also observe the effect of the VLC channel which attenuates the PLC channel frequency response. The PLC-VLC channel also turns to mimic and approximate the low-pass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

We further vary the PLC channel parameters to emulate different PLC environment and frequency response. In Figs. 8(b) and 8(c) we present two other PLC network simulated and the resulting PLC-VLC channel obtained from our model. Fig. 8(b) 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(c), the effect of an increase in number of PLC taps in the network is presented.

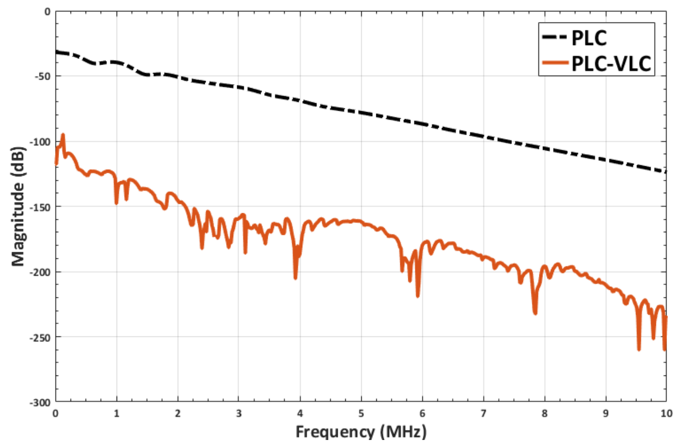
In Fig. 8(d), we superimpose in a single plot multiple PLC channel paths applied through our model. The simulation was done by using the same VLC parameters given in Table 1, and the PLC parameters used where: $a_0 = 0$; $a_1 = 7.8 \times 10^{-10}$, bandwidth = 30 MHz, g and d varying randomly between

TABLE 1: Relevant simulation parameters

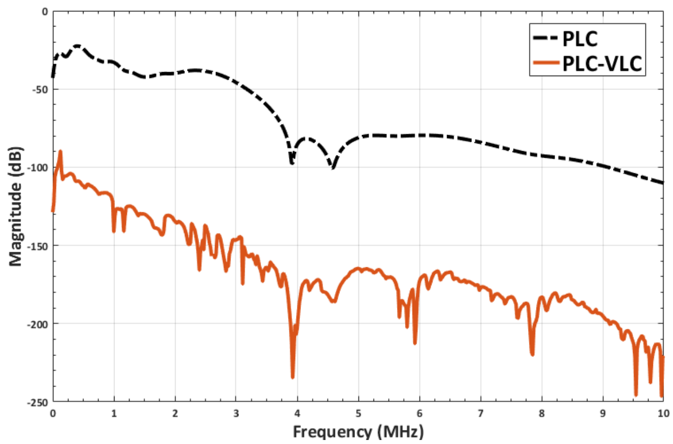
PLC-CHANNEL	
a_0	0
a_1	1.1×10^{-8}
k	1
Bandwidth	10MHz
g	[-0.0039, 0.0156, -0.034, 0.0715,-0.122, 0.076]
d	[78 126 191 256 306 330]
VLC-CHANNEL	
A_{room}	25 m^2
A_r	3 cm^2
L	3 m
f_0	8.3 MHz
Φ	70
Ψ	60
β	0.8
η_{DIFF}	5.3×10^{-6}
η_{LOS}	1.3×10^{-6}



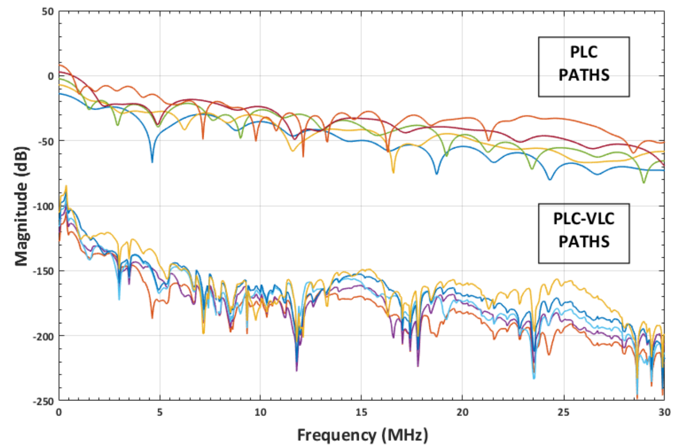
(a) 6 PLC Taps network



(b) 5 PLC Taps network



(c) 12 PLC Taps network



(d) Varying PLC channel paths and Taps with their resultant PLC-VLC channel paths

FIGURE 8: Simulation results of different PLC network with their resulting PLC-VLC channel.

{-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

This paper investigates cascaded hybrid PLC-VLC channels. The PLC and VLC mutual noise scenarios in this system are presented and measurement of the channel frequency response is performed. Primarily the mutual noise scenarios and influence in PLC-VLC channels was analyzed through measurements of the channel frequency response of noise generated by LED supply in both PLC and VLC channel. We characterize three different LED supplies, with independent properties, specifications and topologies. They are used on the same power LED throughout our experiment. We then observed the noise activities in both PLC and VLC channels, for each supply. We presented our results in three frequency sub-bands. The narrow-band PLC frequencies have shown an observable non-linearity with that of the VLC channel whereas, a linear activity is observable in the broadband frequencies. Finally, frequency-dependent PLC noise clipping and attenuation is also observed at the LED supply's output. We further proposed a channel model for hybrid PLC-VLC cascaded systems. The model takes into consideration the effects of the LED power supply which contribute significantly on the overall hybrid channel. 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.

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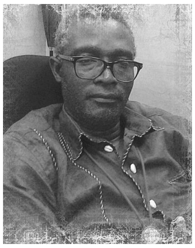

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