Evaluation of the SFSK-OOK Integrated PLC-VLC System Under the Influence of Sunlight

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***Abstract*—With the widespread of light emitting diodes (LEDs) as a primary source of illumination, visible light communication (VLC) offers a lot of potentials by providing both resources and energy saving advantages. This paper presents a practical implementation of an integration of Power Line Communication (PLC) and VLC. The system uses spread frequency shift keying (S-FSK) and on-off keying (OOK) in the PLC and VLC channel respectively. The system is of low complexity, low cost and dedicated to enhance low data rate application of PLC technology. The practical design is compatible with the European Committee for Electrotechnical Standardization (CENELEC) band A and the test are done on a Chinese home environment where the Electric Power Research Institute (EPRI) specifies a 3 kHz to 500 kHz band. Results illustrating the effect of sunlight on this system are presented.**

keywords—*Narrowband PLC, VLC, S-FSK, PLC-VLC, OOK, Hardware implementation*

I. Introduction

Integrated power line communication (PLC) and visible light communication (VLC) systems, onward referred to as PLC-VLC, has recently raised a considerate amount of attention [1]–[6]. This is primarily as a result of the ubiquitous nature and characteristic found in such a combination. The power line cables already used to distribute electricity, is also widely used by PLC technology as a communication medium. The lighting system infrastructure is gradually using light emitting diodes (LED) because of their advantage over incandescent light bulbs. In VLC, the use of LED in lighting systems is exploited into providing ubiquitous networks for communication. VLC is an intensity modulation/direct detection (IM/DD) based communication technology which adds a DC-voltage to a modulated signal to provide both luminance and information transmission through LEDs. PLC-VLC integration therefore both poses communication, energy distribution and illumination capabilities. In addition to that, the presence of their respective infrastructures makes their deployment economically viable, feasible and beneficial. VLC technology provides PLC with the ability to transform its signal into a wireless one [1]. Furthermore, VLC provides PLC with an access to a wide spectrum (380nm-780nm) for communication.

The first idea of integrating PLC and VLC was introduced in [2]. This implemented a single carrier binary phase shift (SC-BPSK) to convey low data rate information. Orthogonal frequency modulation (OFDM) was further used to improve the spectral efficiency of the PLC-VLC integration [1]. The IEEE 802.15.7 [7] is a standard which defines a PHY layer suitable for VLC. This suggests a set of modulation scheme for different scenarios and application based on data-requirement. On-off keying (OOK) modulation is the simplest technique proposed in [7]. OOK, with its low complexity and cost is therefore the best available scheme utilised for VLC systems. In the current state of research involving PLC and VLC integration, a lot of attention is given on broadband PLC and VLC which uses multi-carrier modulation technique. This is successfully being used in broadband broadcasting systems [3]. Such applications where PLC is used as backbone of the communication infrastructure are dedicated to high speed data transmission and are of high complexity and cost [8]. Furthermore, few attention have been placed on narrowband PLC (NBPLC) integration with VLC systems. VLC can be useful in smart home applications [9] whose data requirements are not demanding as in broadband applications. Few practical-orientated works are also currently available to support the PLC-VLC integration. Spread frequency shift keying (S-FSK) [10] is a modulation which combines advantages of FSK with those of spread spectrum systems which low-complexity and narrowband interference immunity respectively [11]. Spread-FSK has eventually been adopted over PLC applications and the IEC 61334-5-1 standard.

The authors in [5] have already proposed a low-complexity PLC-VLC interface between the two technologies. In this paper, we further our development and propose a fully fledge, low-complexity, low-cost and analyse the performance of a PLC-VLC communication system for low-data rate applications utilising S-FSK in PLC and OOK in VLC. Complexity of the system is minimized through the use of simple modulation techniques and further cost of the system is achieved with low cost implementation of the subsystem components such as power supply and PLC coupling. The hardware implemented was safely tested in a live environment at a Beijing apartment. Compliance with EN 5006-1 and IEC 61334-5-1 standards are applied to the prototype design which is operated in the CENELEC-A band. The effect of sunlight radiance as a major source of noise in this system is measured by the luminance at the receiver. This is performed at different instance of the day in order to show the variance of the noise disturbance.

The rest of this paper is organised as follows. Section II gives an overall system description. This is supported by a theoretical background in Section III. Section IV describes the implemented hardware in this study. Results and experimental analysis of Section V precedes the conclusion in Section VI.

II. System Description

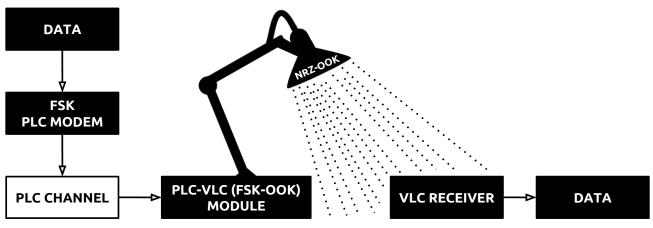


Fig. 1. Overview of system under study

In this section, an overview and brief introduction to the low complexity, low cost integrated PLC-VLC system to enhance low-data rate application is given.

The system presented here is shown in Fig. 1 and uses the indoor 230V/50Hz power line network. Transmitted information bits are processed through a PLC modem which is responsible to convey the information via the power line cables. The PLC modem using S-FSK scheme, modulates, amplifies and superimposes the data signal on the 50Hz AC signal. The data is then conveyed through the power line cables to a receiving point. At the receiver, this information carrying signal is decoupled from the AC line. It is then demodulated and converted to an OOK signal which is then used to drive the LED luminary. The PLC-VLC module effectively converts the electrical signal of the PLC to an optical signal which is needed in VLC. The information carrying signal is therefore intensely modulated or biased through an LED which also provides illumination. This information carrying signal is directly detected by a PD in the VLC receiver and the initial data is recovered.

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. NBPLC operating between 3Hz-500kHz [7] has been characterised by mainly background, impulsive and narrowband noise [12], [13]. VLC is an optical wireless communication and has the light in free space as channel [6]. Noise in VLC therefore originates from other light sources such as sunlight and incandescent or fluorescent light.

The system presented here targets peer-to-peer and low-data rate applications. This PLC-VLC integration could also be found useful in smart-grid communication such as the smart-home technologies presented in [9].

III. Theoretical Background

A. Modulation Scheme

Frequency shift keying is a modulation scheme which transmits digital data through shifting of a carrier frequency to discrete frequencies. Binary FSK (BFSK) being the simplistic form with modulation level $M = 2$, for transmission of data, mark and space frequencies are chosen to represent 1 and 0, respectively. Moreover, BFSK scheme is made coherent by ensuring the initial phases for the two signal used are the same. This provides a continuous signal between bits transition and superior error performance. Thus in general for a coherent BFSK scheme:

$$s(t) = \begin{cases} s_1(t) = A\cos(2\pi f_0 t + \phi) & 0 \le t \le T_b, \\ s_2(t) = A\cos(2\pi f_1 t + \phi) & 0 \le t \le T_b, \end{cases} \tag{1}$$

where ϕ is the initial phase at $t = 0$ and A is the amplitude.

Spread FSK (S-FSK) modulation is a technique employed on the IEC-61334-5-1 PHY layer which requires $|f_0 - f_1| > 10kHz$. This adds robustness to the FSK scheme and reduces the chances of narrowband interference.

On-off keying modulation is the simplest form of amplitude shift keying. Its selection in our proposed system is tied to its good bandwidth efficiency, simplicity and ease of implementation. In OOK, bits are encoded by transmission for a time T for a bit 1 and not transmitting for the same period when it is a 0.

In order to implement a IM/DD scheme, VLC requires a real and non-negative signal. Two voltage levels "0" and "A" are used in VLC to form a square wave. The mapping in (2) is performed whereby, the space and mark frequencies represent the voltage levels "0" and "A", respectively. In other words, the FSK modulator's output corresponds to the input of the OOK modulator.

$$\begin{cases} s_1(t) = A\cos(2\pi f_0 t + \phi) \implies & 0, \\ s_2(t) = A\cos(2\pi f_1 t + \phi) \implies & A. \end{cases} \tag{2}$$

B. PLC-VLC Integration

Fig. (2) shows a measured channel response of a NBPLC channel. The channel is different from an additive white gaussian noise (AWGN) [12], which is popularly used to model communication channels.

The VLC channel is modelled as a linear optical AWGN channel given in (3). This relates the instantaneous transmitted optical power $P_t(t)$ to the detected instantaneous current $I_p(t)$ using the channel impulse $h(t)$ and noise component $n(t)$.

$$I_p(t) = RP_t(t) * h(t) + n(t) \tag{3}$$

where $*$ denotes convolution.

The VLC transfer function is modelled by a line-of-sight (LOS) and a non-line-of-sight (NLOS) component [14].

$$H_{vlc}(f) = \sum_{i=1}^{N} \eta_{LOS,i} e^{-j2\pi f \Lambda_{LOS}} + \frac{\eta_{DIFF}}{1 + jf/f_0} e^{-j2\pi f \Lambda_{DIFF}} \tag{4}$$

In (4) 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], [14].

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.

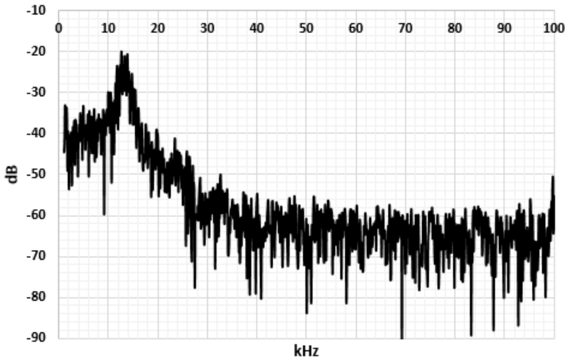


Fig. 2. Measured spectrum of PLC over CENELEC A-Band

C. Noise and Interference

The presented system being an integration of two independent communication channels which are cascaded. This will result in the superposition of their respective noise components.

The noise model assumed over the NBPLC is a cyclostationary additive Gaussian noise with zero mean and its variance synchronous to the mains AC voltage [12]. This model is made up of the time dependant instantaneous noise power (5) and frequency dependant power spectral density (6).

$$\hat{\sigma}(t) = \sum_{l=0}^{L-1} A_l |\sin(2\pi t/T_{AC} + \theta_l)|^{n_l} \quad (5)$$

$$\alpha(f) = \frac{a}{2}\exp(-a/|f|) \quad (6)$$

Equations (5) and (6) make up the variance (7) of the power line noise [12].

$$\sigma^2 = \hat{\sigma}(t)\alpha(f) \quad (7)$$

In (5), the parameters A_l, θ_l and n_l are extracted from a measured time domain noise measurement.

VLC channel on the other hand, is characterised by thermal and shot noise [2], [6]. Shot noise is as a result of other light sources and can be modelled by Poisson distribution.

IV. Hardware Implementation and Description

A. FSK-PLC Transmitter

The PLC transmitter implemented is a coherent binary FSK. Two discrete frequencies are selected within the CENELEC A Band. From the measure channel response of Fig. 2, favourable frequencies with lesser noise components are located above 30 kHz.

Important design steps were applied on the coupling interface. This ranges from impedance matching to winding ratio suggested by previous studies [15] is applied here. Fig. 3 shows the designed hardware prototype showing its various blocks components.

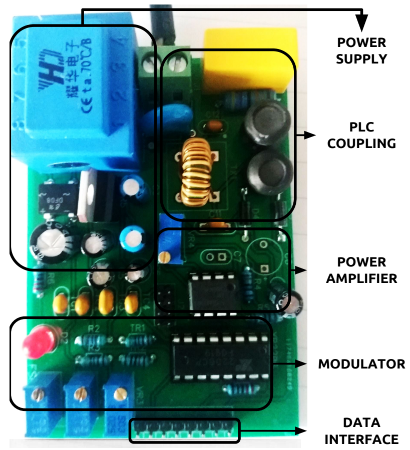


Fig. 3. FSK-PLC Module

B. PLC-VLC Module

The PLC-VLC module's input is expecting a S-FSK signal. In order to capture this analog signal, a monolithic phase locked loop (PLL) detector is implemented. Phase locked loop is a common frequency and phase sensitive control circuit used for FSK demodulation. The signal originating from the powerline cable has to primarily be captured by a coupling circuit. Different alternatives to circuit coupler unit exist. However, for cost and size constraints, a passive, transformerless coupling circuit presented in [16] is a viable choice. Fig.4 shows the response of the T-shaped band pass filter (coupling circuit) used on the module. This clearly illustrates the bandwidth availability for the signal reception over the CENELEC A-Band. The module is further equipped with a transient voltage suppressor (TVS) and a metal oxide varistor (MOV) which are protective components for both the module and its users. The last section of this module comprises of an led driver implemented using a MOSFET transistor. The final prototype of the module is displayed in Fig. 5. The prototype is in low cost, complexity and power usage. It is operated at 12V and its maximum current is 500 mA which is the peak the supply can generate. The supply of this modules imposes a constraint on the LED rating which it can drive for data transmission and illumination.

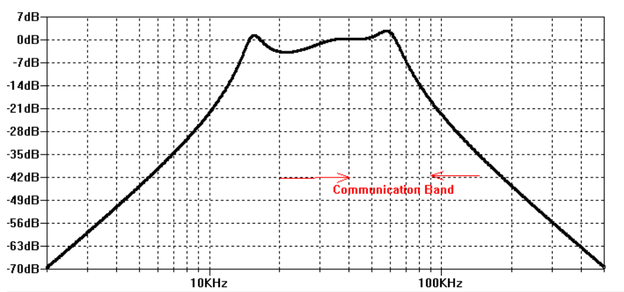


Fig. 4. Simulation of PLC Coupling implemented on the PLC-VLC module.

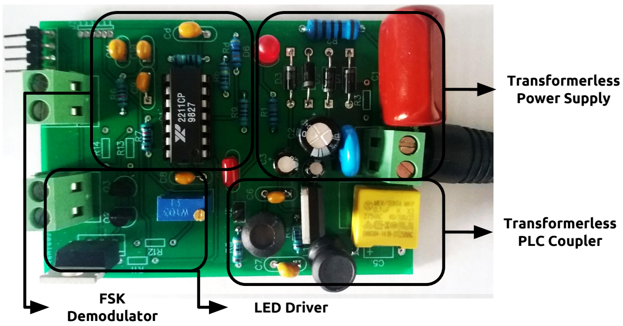


Fig. 5. Hardware PLC-VLC Module depicting its low-cost and low-complexity components composition.

C. VLC Subsystem

In VLC systems, LEDs and the photodetectors (PD) are transmitter and receiver respectively [6]. The VLC subsystem consist of an LED as transmitter and a PD as receiver. The LED used is a desk-lamp which consist of a 3W 4×8 LED matrix. The photo diode used to receive the OOK transmitted signal was Vishay BPW34. Its sensitivity is suitable enough for its purpose as illustrated by its spectral sensitivity shown in Fig 6. The receiver implemented here is a simple illustration since the VLC receiver is not study on this paper. Further informations can be found in [17], [18].

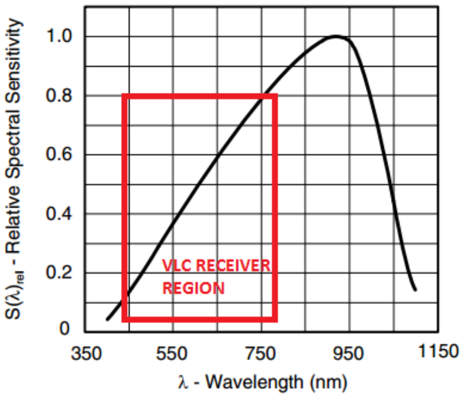


Fig. 6. Spectral Sensitivity of PD used, showing the highlighted region necessary for VLC data detection.

V. Experiments and Results

The set-up used in this section is shown in Fig. 7. The FSK-PLC module is connected to the mains and interface by a signal generator which emulates data information using a square wave. The modulated signal is then amplified and transmitted through the power line cable. The S-FSK signal measured prior to transmission is displayed in Fig. 8.

The PLC-VLC module described in Section IV above detects and drives an LED which conveys the initial data sent. The S-FSK frequencies used in the test were 35 kHz and 70 kHz for space and mark frequencies respectively. The optical signal is recovered using the VLC receiver. Luminance of the LED lamp is measured using a TASI8123 digital lux light meter at the receiver at different instance of the day. Distance between the transmitting PLC-VLC module and the PD VLC receiver is varied and results shown in Fig. 9. The room used consisted of a single window through which sunlight irradiance penetrates. The tests are performed during daytime with LOS maintained between the transmitter and VLC receiver. Though the sunlight irradiance is not quantified, its noise component on the NLOS path affects the received signal. Considerable amount of noise is observed on the receiver. This gradually increases with time of the day. By midday a maximum amount is reach. With LOS maintain and the separation between the transmitter and PD kept below 50 cm, the data is still received with few disturbances. Background noise with increase in separation and time of the day is also observed. These observations suggests that there is a safe margin of separation that can be obtained at a specific day time. Further room for investigating the sunlight irradiance in this integrated system has to be done by also considering the noise propagation from the PLC channels which will be investigated in future works.

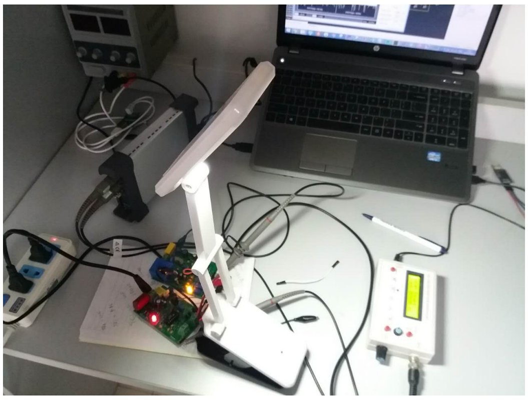


Fig. 7. Measuring set-up consisting of a signal generator, HANTEK6052BE PC-OSCILLOSCOPE and including the FSK-PLC module + PLC-VLC module both connected to the powerline.

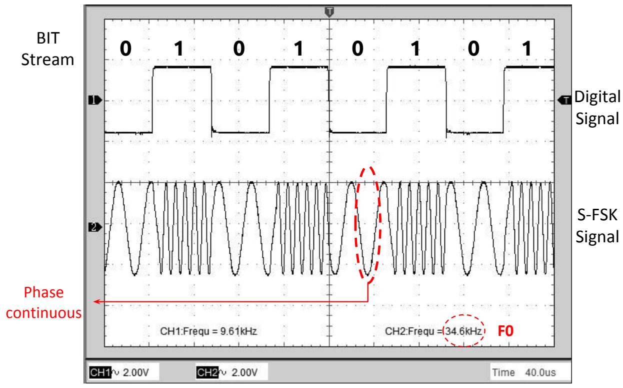
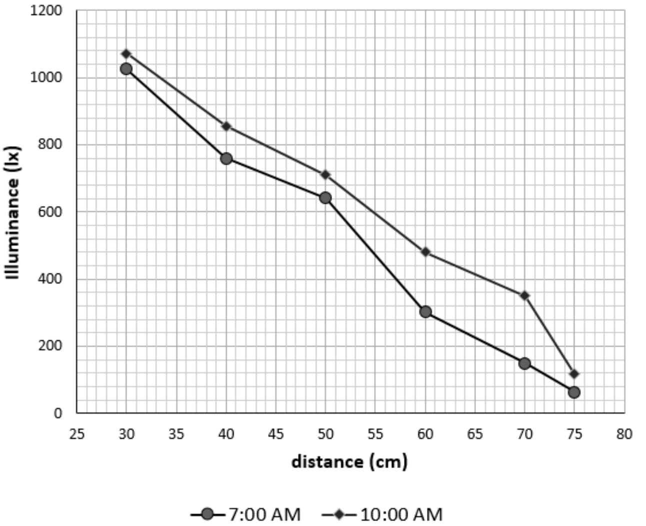


Fig. 8. Measurement of the FSK-PLC Transmission showing the input data and the modulated signal coupled to the PLC channel.



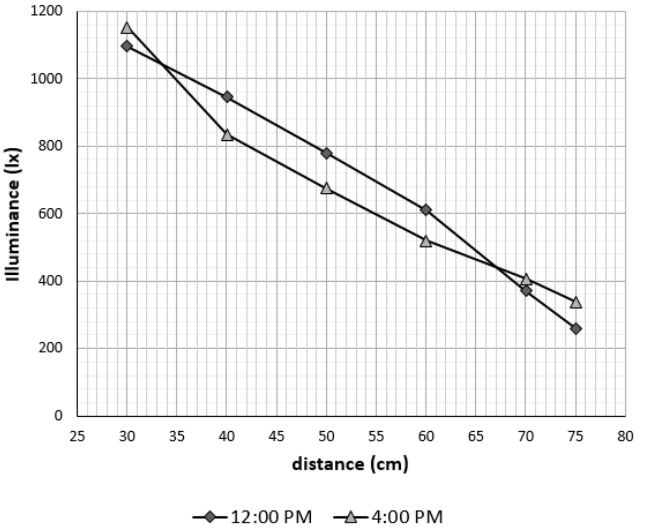


Fig. 9. Measured illuminance against distance between the LED transmitter and receiver at different time of the day.

VI. Conclusion

This paper presents an integration of Narrowband PLC and VLC technology utilising spread binary FSK and on-off Keying modulations. The system is a low cost, low complexity and low data rate driven solution. The model of the system is discussed and a hardware implementation of this integrated system is presented. Sunlight irradiance is a major source of noise on this integration. The effect of sunlight irradiance at four different time of the day is measured and discussed.

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