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Visible light wireless data communication in industrial environments

S Riurean[1,*], M Leba[1], A Ionica[1], O Stoicuta[1] and C Buioca[1]
[1]University of Petrosani, 20 Universitatii str, 332006, Petrosani, Romania

E-mail: simonariurean@upet.ro

Abstract. Significant implementations and encouraging results have already been achieved using visible light communication (VLC) technology for different applications from indoor to free space optics (FSO) and even underwater communication. The LED light fixtures are about to be used with dual functionality - illumination and fast wireless data communication - and when the technology will become mature enough, the general costs for both will considerably decrease. However, especially due to a complex multipath channel impulse response (CIR) evaluation, there are few research in VLC applied in industrial environments. At the same time, in the non-Line of Sight (NLoS) VLC setup with mobile optical transmitter (oTx) and fixed optical receiver (oRx) considered here, both the path loss and multipath-induced dispersion significantly limits the link performance. In this paper, we investigate the CIR into indoor industrial environments. We take into consideration both Intrinsic Optical Properties in Industrial Environments (IOPIEs) and Apparent Optical Properties (AOPs) in Industrial Environments. The VLC setup complexity such as oTx and oRx position and orientation, the geometry and the nature of the indoor surfaces (diffuse or specular) and appropriate positioning of both oTx and oRx required for a suitable implementation of the VLC. The VLC system proposed is also investigate in this work based on data acquisition, simulation and analysis according the ARX mathematical model.

1. Introduction

The incredible, unprecedented increasing data rate demands of the wireless smart devices require new technologies to release the overwhelmed radio frequency (RF) domain of the electromagnetic spectrum.

During the last decade, both researches works and funds invested in different projects of optical wireless communication (OWC) technology has been more enthusiastic than ever. OWC denotes any kind of transmission based on light as communication wireless medium. Infra-Red (IR), Visible Light Communication (VLC), Free Space Optical (FSO) as well as LiFi are all part of the OWC.

VLC refers to an artificial light source, a Light Emission Diode (LED) that sends indoor data, piggybacked by illumination.

FSO communication, analogous to VLC, covers additionally, the IR and ultraviolet (UV) spectrum, it doesn’t have an illumination requirement, therefore, communication links between buildings is a good example of proper application.

LiFi can be described as a fully networked light transmission based on the illumination fixture with high speed, full duplex, Multiple Input Multiple Output (MIMO) users, equivalent to Wi-Fi with the exception that, for communication is used light instead of radio [1].

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VLC due to the progress of solid state lighting (SSL) and the potential of simultaneously using LEDs both for illumination and wireless data communication consists in a great benefit for indoor communication [2].

The performance of GaN blue with phosphor-layer, white LEDs (WLEDs) that have longer lifetime, energy efficiency and high tolerance to both humidity and extreme temperatures will soon drive to globally replace the existing fluorescent, halogen or incandescent bulbs in lighting fixtures. Such a trend will also be a great opportunity for optical wireless communication (OWC) technology to be largely deployed in many areas from offices to homes, healthcare and more important, industry domain. Data communication in optical wireless transmission is possible through Intensity Modulation/Direct Detection (IM/DD) technique of the incoherent light sources. Moreover, important advancements have lately been noticed in optoelectronic devices for visible light communication (VLC) technology and modulation techniques. VLC technology has a promising, bright future since it is a reliable alternative solution to wireless data communication based on radio frequency transmission [3].

Trichromatic (RGB) LEDs (TLEDs) as well as quad-chromatic LEDs (QLEDs) based on Colour Shift Keying (CSK) allow to achieve high data-rates using multiple channels in visible spectrum. The conventional TLED with CSK, standardised by IEEE 802.15.7 (1), provides up to 96 Mbps for a 24 MHz system bandwidth. This standard is currently under revision as the VLC physical layer (PHY) performance is about to be improved. Important milestones have been noticed both on Visible Light Communication (VLC) standardisation and Light Fidelity (LiFi) technology (2). LiFi has been coined by professor Harald Haas at TED Global in 2011. This presentation is considered as one of the milestones in OWC technology. During his live presentation, professor Haas made both a lexical connection to Wi-Fi and a practical demonstration of the data communication by sending a high definition movie through light using a desk lamp.

Both the Positive Intrinsic Negative (PIN) and Avalanche Photodiode (APD) (with fast rise and fall times, high responsivity and small active area) are the most suitable off-the-self photodetectors (PDs) used for proper OWC setups [4].

2. Considerations on light beam propagation in industrial environments

The light beam that propagates in polluted environments, as industrial environments are, upon interaction with the tiny particles in suspension suffer from low to even sever attenuation because of both absorption and scattering phenomena. Absorption removes the photons permanently from the path, while scattering redirects the angle of the photon path deviating the light from its initial direction. Absorption, unlike scattering, is extremely spectrally dependent. Parts of the light intensity is absorbed and converted into other forms of energy. The two light' characteristics, scattering and absorption are both present into an industrial polluted environment.

Absorption is a permanent loss of optical power as long as light propagates in the polluted environment. It occurs due to the photons' interaction with suspended molecules and particles find in the light's way from the optical transmitter (oTx) to the optical receiver (oTx). Absorption depends on the variation of the medium refraction index (n) and wavelength of the light (λ).

Scattering, defined as the deflection of light from its original path is the light' property most evaluated into polluted industrial environment. On the microscopic level, scattering relates to the interaction between a light photon and a molecule or an atom. Moreover, particles of different type of material with different shapes, concentrations, humidity effectively determine the scattering properties of the medium.

In fact, even in small concentrations, these particles make the scattering highly peaked in the forward direction, which is one of the major characteristics of the visible light propagation in polluted medium.

The performance of an Industrial Wireless Optical Communication (IWOC) system is highly affected by channel fading as a result of air movement with tiny particles in suspension.

This is similar to the atmospheric turbulence in FSO communication when fog and rain are also considered. Spots of polluted, movement air, with suspended particles with different shapes and sizes continuously change the propagation direction of photons due to the variation of refraction index, *n* [5].

2.1. Intrinsic and Apparent Optical Properties

Light properties into industrial environments can be separately described as intrinsic and apparent.

Light's Intrinsic Optical Properties (IOPs) depend exclusively by the medium.

Apparent Optical Properties (AOPs) are dependent both of the medium and the environment studied. The environment studied refers to the surrounding within the its space particularities: natural and/or artificial light, geometrics, type of materials and colour of the objects within the space where the OWC setup is considered.

The IOPs are conservative properties and hence the magnitude of the absorption coefficient linearly varies with the concentration of the absorbing material.

Theoretically, the absorption coefficient can be expressed as the sum of the absorption coefficients of each component in the polluted air [6].

2.2. Optical Properties in Industrial Polluted Environments

The two Intrinsic Optical Properties in Industrial Environments (IOPIEs) that model light absorption and scattering are both the function of Spectral Volume Scattering (SVS) $\beta(\theta,\lambda)$ and the coefficient of spectral beam absorption $a_s(\lambda)$ in [m^{-1}].

The SVS, refers to the part of incident power scattered out of the beam with the θ angle. The coefficient of beam spectral scattering $b_s(\lambda)$ in [m^{-1}] results as the integration of the SVS in all directions:

$$b_s(\lambda) = 2\pi \int_0^{\pi} \beta(\theta,\lambda) sin\theta \, d\theta \tag{1}$$

The volume scattering phase function is:

$$\tilde{\beta}(\theta,\lambda) = \frac{\beta(\theta,\lambda)}{b_s(\lambda)} \tag{2}$$

The spectral beam attenuation coefficient $c_a(\lambda)$ considered also as optical power annihilation is:

$$c_a(\lambda) = a_s(\lambda) + b_s(\lambda) \quad [m^{-1}] \tag{3}$$

Integrating the SVS in the range [$\pi/2$, π], the backscattering coefficient b_{bs} in [m^{-1}] is obtained [6].

Fermat's principle, also called the principle of least time, states that optical rays of light traverse the path of stationary optical length with respect to variations of the path, meaning that rays take the path that requires the least travel time. Clean air has the refraction index n_2=1 but the air into industrial environments is usually filled with tiny suspended particles within the air that continuously moves.

Light beam attenuation or transmission loss, denotes to the intensity of the light from the LED that decreases with distance respect to the PD into the aimed communication medium.

Attenuation coefficients through the medium (in units of dB/m) is:

$$A = 10 * log_{10} \frac{I_{input}}{I_{output}} \ (dB) \tag{4}$$

In reality, the industrial environment has lots of drawbacks when we analyse it from the optical channel behaviour point of view, in order to be applied for a VLC efficient setup. A specific (well determined) level of artificial light coming from different other sources (as lighting fixtures, for example) as well as the natural light, result in Additive White Gaussian Noise (AWGN) that can be particularly determined. Position of the LED embedded into the oTx, as well as PD embedded into the oRx can be clearly determined for clean air and a Line of Sight (LOS) topology with a short distance between LED and PIN PD for a proper, performant VLC setup.

In order to study and model the optical channel impulse response (CIR), both IOP and AOP characteristics have to be considered in industrial environments. Root mean square spread delay (RMS-DS) is not going to be taken into consideration in this work for the CIR since the optical path considered is for a setup LOS topology with high optical attenuation (due to light's absorption and scattering).

Position (on the path of optical beam - between LED and PD), geometrics, colours, materials (wood, steel, fabric or painted objects for example) and type of surfaces of the object inside (matt or glossy, smooth or rough) into the industrial hall are also very important environmental characteristics of the optical channel from the AOPs point of view.

A proper design of the optics (shape, dimension and type of LENS) both in front of LED as well in front of the PIN PD are clearly very important, in order to achieve higher distance between oTx and oRx with high data rates and a better optical signal acquisition for a well-organized VLC with a LOS topology.

Since all the characteristics of IOP and AOP in industrial environments cannot be measured or proper calculated based on a general, comprehensive mathematical model, a proper estimation is possible to be done based on data acquisition during a wireless transmission based on visible light.

3. The VLC prototype and LOS setup

A VLC prototype (both oTx and oRx) has been developed in order to send and receive data by visible light at different distances with different data rate.

Both electronic circuits for oTx and oRx on the breadboards can be seen in Figure 1.

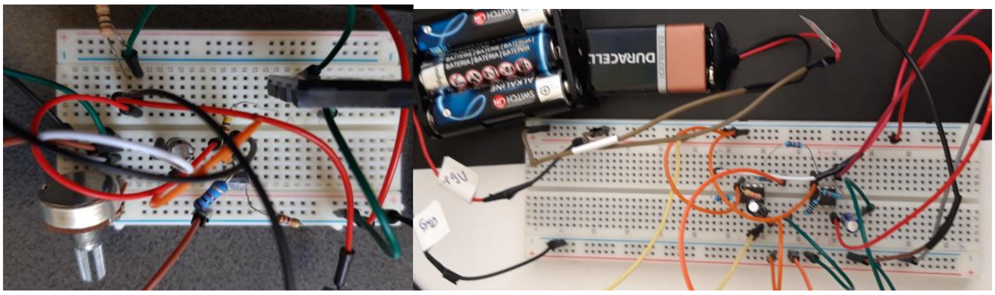

Figure 1. Electonic setup oTx (left) and oRx (right).

The equipment used to generate, display and acquire data consists of a function generator type MFG – 8216A and an oscilloscope type UPO2104CS as can be seen in Figure 2.

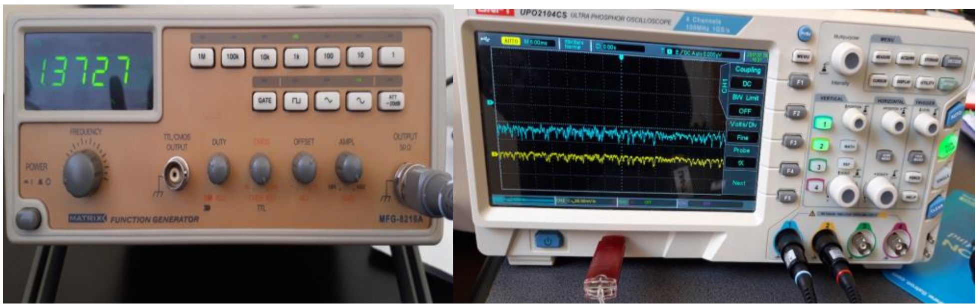

Figure 2. The function generator MFG – 8216A (left) and oscilloscope UPO2104CS (right) used for data acquisition.

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The final VLC prototype during tests is shown in Figure 3.

Data have been acquired during VLC data transmission and stored as *.csv files on the stick inserted into USB port of the oscilloscope. The *.csv files have been then converted in order to be used as base information for an extended simulation and analyses done with the Eviews 10 software support.

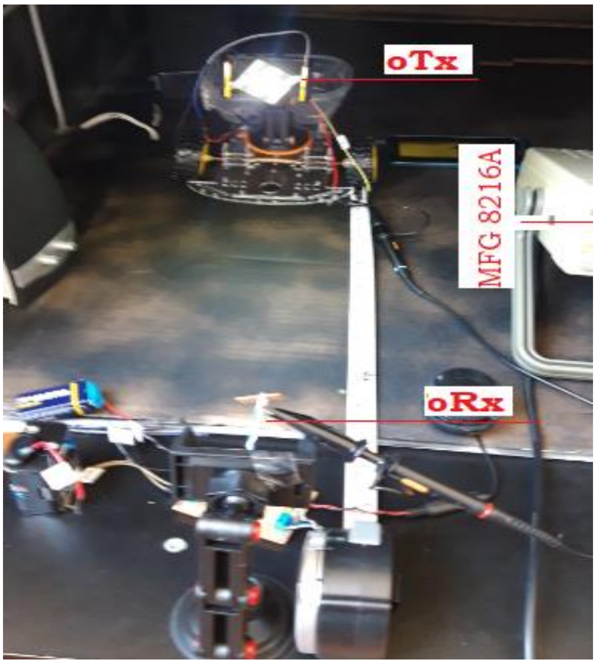

Figure 3. The VLC prototype developed to send data based on visible light. The optical transmission module (oTx) with its electronic setup and 1Watt white cold LED, the optical receiving module with its electronic setup and a PIN PD, as well as the function generator MFG – 8216A.

4. Data acquisition and ARX model analyses

Data have been acquired (during communication based on visible light) and stored as *.csv files on the stick inserted into USB port of the oscilloscope. The *.csv files have been then converted to *.xls format and used as base information for an extended analyses done with the Eviews 10 software support.

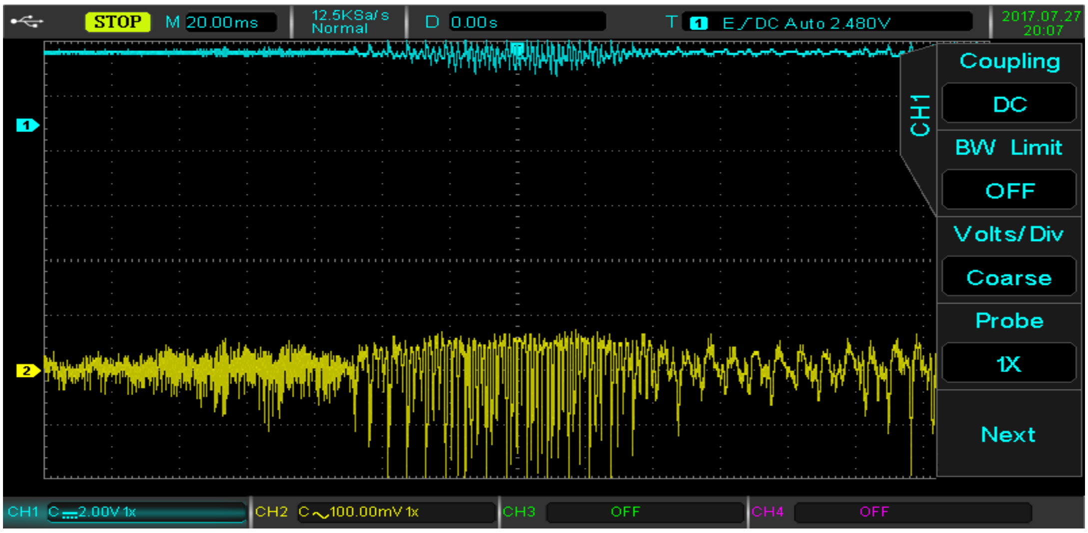

Figure 4. Signals sent (channel 1 blue/up) and received (channel 2 - yellow/down) displayed on the oscilloscope screen.

Data acquired and analysed are presented in Table 1.

Table 1. Data analysed with Eviews software.

Dependent Variable: YA
Method: Least Squares
Date: 04/20/19 Time: 12:01
Sample (adjusted): 26 100
Included observations: 75 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
UA	0.409548	0.080228	5.104817	0.0000
UA(-1)	0.155415	0.110339	1.408518	0.1718
UA(-2)	-0.067525	0.113482	-0.595023	0.5574
UA(-3)	-0.358969	0.113949	-3.150255	0.0043
UA(-4)	0.098018	0.130212	0.752755	0.4589
UA(-5)	0.017442	0.127617	0.136675	0.8924
UA(-6)	0.059017	0.131389	0.449178	0.6573
UA(-7)	0.023159	0.132004	0.175443	0.8622
UA(-8)	0.046535	0.123530	0.376710	0.7097
UA(-9)	0.087375	0.120678	0.724033	0.4760
UA(-10)	-0.158562	0.120953	-1.310938	0.2023
UA(-11)	-0.094388	0.116117	-0.812866	0.4243
UA(-12)	0.014529	0.113338	0.128194	0.8991
UA(-13)	0.041022	0.112011	0.366233	0.7174
UA(-14)	0.189087	0.111766	1.691811	0.1036
UA(-15)	-0.217951	0.127073	-1.715167	0.0992
UA(-16)	0.130822	0.128326	1.019451	0.3182
UA(-17)	-0.077746	0.130366	-0.596367	0.5565
UA(-18)	-0.181451	0.119279	-1.521229	0.1413
UA(-19)	-0.083728	0.116857	-0.716500	0.4806
UA(-20)	0.031608	0.112567	0.280791	0.7813
UA(-21)	0.066835	0.108730	0.614692	0.5445
UA(-22)	-0.238185	0.108630	-2.192636	0.0383
UA(-23)	0.063933	0.107087	0.597021	0.5561
UA(-24)	-0.131968	0.102794	-1.283820	0.2115
UA(-25)	0.173111	0.096742	1.789415	0.0862
YA(-1)	0.191010	0.170834	1.118103	0.2746
YA(-2)	0.125182	0.160318	0.780840	0.4425
YA(-3)	0.515259	0.168918	3.050356	0.0055
YA(-4)	-0.443199	0.197946	-2.238984	0.0347
YA(-5)	0.026109	0.194786	0.134039	0.8945
YA(-6)	-0.404687	0.196726	-2.057109	0.0507
YA(-7)	0.098673	0.202161	0.488091	0.6299
YA(-8)	-0.068035	0.190939	-0.356321	0.7247
YA(-9)	0.084199	0.188856	0.445837	0.6597
YA(-10)	0.310659	0.188079	1.651743	0.1116
YA(-11)	-0.226928	0.188214	-1.205688	0.2397
YA(-12)	-0.023842	0.166739	-0.142991	0.8875
YA(-13)	-0.043527	0.173909	-0.250286	0.8045
YA(-14)	-0.020433	0.175039	-0.116732	0.9080
YA(-15)	0.069437	0.170073	0.408277	0.6867
YA(-16)	-0.163556	0.172398	-0.948715	0.3522
YA(-17)	0.031781	0.174303	0.182334	0.8569
YA(-18)	0.393100	0.168653	2.330821	0.0285
YA(-19)	-0.052877	0.174632	-0.302790	0.7647

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Variable	Coefficient	Std. Error	t-Statistic	Prob.
Variable	Coefficient	Std. Error	t-Statistic	Prob.
YA(-20)	-0.097136	0.167498	-0.579923	0.5674
YA(-21)	-0.187870	0.171863	-1.093138	0.2852
YA(-22)	0.174134	0.167252	1.041150	0.3082
YA(-23)	-0.032103	0.161902	-0.198286	0.8445
YA(-24)	0.308557	0.175433	1.758834	0.0914
YA(-25)	-0.507815	0.166249	-3.054537	0.0054

R-squared	0.926315	Mean dependent var	-0.008320
Adjusted R-squared	0.772806	S.D. dependent var	0.136124
S.E. of regression	0.064883	Akaike info criterion	-2.411893
Sum squared resid	0.101036	Schwarz criterion	-0.836001
Log likelihood	141.4460	Hannan-Quinn criter.	-1.782657
Durbin-Watson stat	2.117332		

As part of the system identification, the Least Squares Method (LSM) is used to define the deterministic part model of a disrupted system using the mean square modelling error [7].

The model type considered here is ARX (autoregressive controlled or with exogenous values) defined by the following equations:

$$A(q)\cdot y(t) = B(q)\cdot u(t-k) + e(t) \tag{5}$$

where:

$$A(q) = 1 + a_1 \cdot q^{-1} + a_2 \cdot q^{-2} + \cdots + a_{na} \cdot q^{-na} \tag{6}$$

$$B(q) = b_1 \cdot q^{-1} + b_2 \cdot q^{-2} + \cdots + b_{nb} \cdot q^{-nb} \tag{7}$$

- k - the dead time expressed in a number of sampling periods;
- e(t) - the prediction error;
- t – the normalized time (real time divided by the sampling period), the values from the set of integers $t \in \mathbf{Z}$;
- u(t) the Input value at the time t;
- y(t) the Output value at time t;
- q^{-1} one-step delay operator;
-

$$q^{-1} \cdot u(t) = u(t-1) \tag{8}$$

and accordingly:

$$q^{-k} \cdot u(t) = u(t-k). \tag{9}$$

- a_i; $i = \overline{1,na}$ and b_j; $j = \overline{1,nb}$ parameters to be identified for the ARX model.

In this specific case, the degree polynomials of A and B are *na* = *nb* = *25* and coefficients are according to Table 1.

The ARX model given by the relationship (5) is a single-variable model valid for SISO (Single Input Single Output) systems.

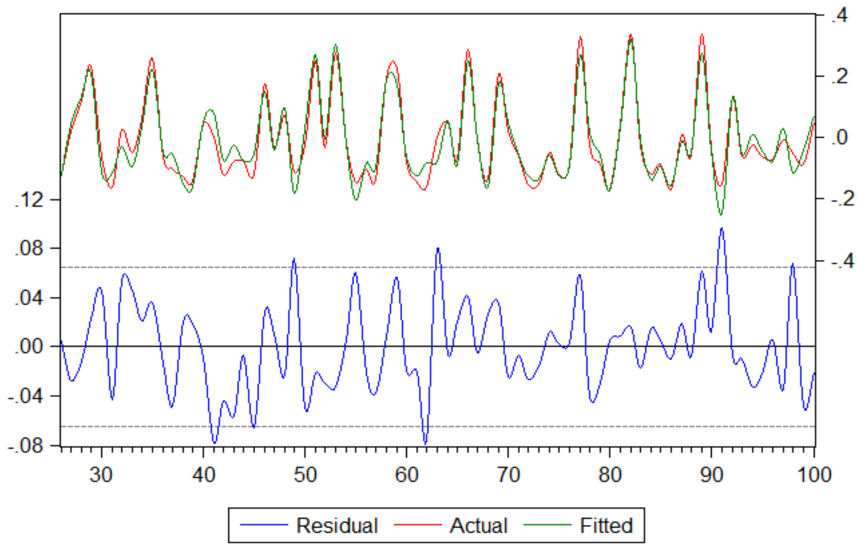

Figure 5. Simulation results (red- real data acquired, green – estimated data, blue- error).

When the parameters determination is finished due to the entire measurements series processing, both for the input and output data of the system considered, the identification is an off - line parametric one.

The simulation results are presented in Figure 5.

5. Conclusions

Important implementations and results achieved with VLC technology into diverse areas have been already deeply investigated the last decade. The LED light fixtures will soon be used not only for illumination but for fast wireless data communication, also. Up till now, due to a complex multipath CIR difficult evaluation and estimation, there are few theoretical researches in VLC technology applied in industrial environments. In this work we take into consideration both Intrinsic Optical Properties in (IOPs) and Apparent Optical Properties (AOPs) in industrial environments. The VLC setup complexity industrial environments increase with the polluted air since the optical path suffer from high loss because of both scattering and absorption optical properties. Since all these data are not persistent during a certain period of time and cannot be proper estimated, a VLC prototype has been developed and tests in laboratory have been done in order to acquire specific data both from oTx and oRx to simulate the entire VLC system.

According to data acquired and time series studied for both input and output data for the VLC system with LOS topology, based on Eviews software, an ARX mathematical model results. The determination coefficient (R^2) is higher than 0.9 as can be seen in Table 1, therefore a high quality ARX mathematical model results. This ARX mathematic model gives an accurate model regarding the VLC setup for a LOS topology in places with polluted medium, as the industrial environment is.

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