Active Pre-Equalizer for Broadband over Visible Light

Tomas STRATIL[1], *Petr KOUDELKA*[1], *Radek MARTINEK*[2], *Tomas NOVAK*[3]

[1]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[2]Department of Cybernetics and Biomedical Engineering, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[3]Department of General Electrical Engineering, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic

tomas.stratil@vsb.cz, petr.koudelka@vsb.cz, radek.martinek@vsb.cz, tomas.novak1@vsb.cz

DOI: 10.15598/aeee.v15i3.2210

Abstract. *This paper introduces a new technology called Broadband over Visible Light (BVL) which combines two technology solutions like Visible Light Communication(VLC) and Broadband over Power Line (BPL). This new technology is suitable for converting modern LED lighting systems into communication systems. However, there are some deficiencies in BVL technology such as the low bandwidth of LED optical transmitters. Pre-equalization may be solution of this problem. This paper proposes higher bandwidth using the pre-equalization circuit. Also, it shows real experimental results demonstrating an improvement of bandwidth and transmission rate.*

Keywords

Equalization, Labview, pre-equalizaton, Software-defined radio, Visible Light Communication, VLC.

1. Introduction

The recent development in the area of white LEDs caused their common use as a highly efficient alternative to the conventional sources of optical radiation in the visible range. This development brought progressive changes in the lighting technology. The physical principle of white LEDs allows their use for communication purposes. The physical principles, including changes in trends of the lighting technology, caused the emergence of a new research direction generally called Visible Light Communication (VLC), which is a derivative of original research direction generally known as indoor Optical Wireless Communication (indoor OWC), operating exclusively in the infra-red spectrum of optical radiation. The objective of this research direction is merging lighting and communications [1], [2] and [**?**].

The Broadband over Visible Light (BVL) is a new research direction based essentially on VLC technology. Again, it is intended to utilize the visible spectrum of optical radiation as a communication direction to the end user (downlink) and to utilize the infra-red spectrum of optical radiation (940 nm) in the reverse communication direction (uplink). Moreover, compared to the VLC concept, in the case of BVL, it is intended to use the chipset of the Broadband over Power Line (BPL) technology, which, inter alia, allows the use of the OFDM MQAM modulation format at the number of 1155 sub-carriers in the frequency range from 2 MHz to 32 MHz (for example HomePlug AV). The BVL technology should, by its nature, enable transmission speed of 100 Mb$\cdot$s^{-1}. Additionally, the BVL technology provides connectivity over power conductors in an efficient way. It gives us the opportunity to transmit the modulated signal to the optical transmitter by its power lines, and use visible light as a wireless data transmitter.

White light LEDs as transmitters for communication link have the big disadvantage as low bandwidth. Low bandwidth is caused by optoelectronic response of the LED and due to physical principles of fluorescence in a thin layer of phosphor which is responsible for creating white light from blue light. Fluorescence inserts some delay to the optical signal and thus influences the maximum bit rate. White power LEDs achieve several MHz of bandwidth [8]. Some researchers achieve

10 MHz of bandwidth due to optical band pass filter on detection side, where only blue part of wavelength processes pass on photodetector without delayed yellow part from fluorescence. Equalization techniques are used for elimination of LEDs optoelectronic response to achieve higher bandwidth [6] and [7]. This article deals with this actual issue and brings new unpublished results, which can help to develop BVL technology.

2. Bandwidth of LEDs

Broadband Power Line technology operates in the frequency range from 2 MHz to 32 MHz at HomePlug AV specification and provides a 200 Mb·s^{-1} PHY channel rate and 150 Mb·s^{-1} information rate. Suitable bandwidth of optical transmitter has to be reached for cooperating HomePlug AV specification with VLC. The frequency response of high power light LED Philips Fortimo LED DLM 3000 44 W/830 was measured. Network analyzer Rhode-Schwarz ZVB 4 (3 kHz to 4 GHz) [9] was used with our own designed circuit Bias-T [12]. PIN photodetector Thorlabs PDA10A-EC was applied on detection side. Philips Fortimo LED DLM 3000 44 W/830 has system efficiency 62 lm/W. This LED light source offers an advantage for VLC measuring and testing, because of its concept of construction. There were used blue LED chips, which are directly placed on the aluminum block for effective cooling. External diffuser in front of blue LED chips converts part of blue (lower) wavelengths range into higher wavelengths due to phosphor layer as seen in Fig. 1. This white light LED has patented remote phosphor technology. This LED light source meets requirements for future duplex communication. Photodetector operating in the infrared wavelength range could be used behind diffuser with the phosphor layer. Measured values of frequency response were fitted by cubic function to

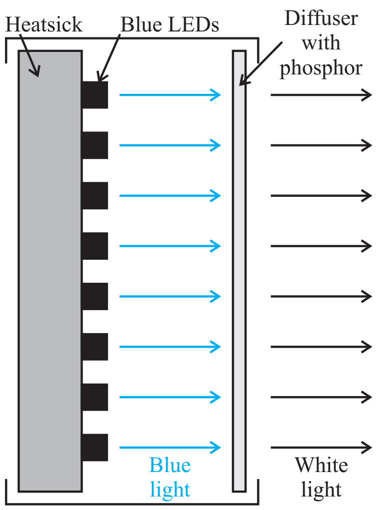

Fig. 1: Concept of Philips FORTIMO LED DLM 3000.

eliminate roughness caused by noise and other signal distortion. The smoother curve of frequency response provides ideal conditions to design the pre-equalization circuit. −3 dBm bandwidth was achieved at 2 MHz with a high power white light LED as shown in Fig. 6, and at 7 MHz with blue part of radiation without phosphor effect.

2.1. Design of Pre-Equalizer

The purpose of equalization is to compensate signal distortion in a communication channel. The main distortion of the signal was produced by the optical transmitter at VLC channel due to an optoelectronic response of LED and delay of the phosphor [6]. We used well-known equalization techniques and techniques for designing filters to reach suitable bandwidth. Appropriate bandwidth was reached with a really simple electronic circuit, because the simplicity of designed circuit was the important requirement.

Pre-equalization circuit was designed according to the reversal of measured frequency response, which can be seen in Fig. 6. The circuit is composed of an active and mainly passive part, which determines shape of frequency response. The passive part of the circuit is high pass filter, which causes 35 dBm attenuation, as it can be seen in Fig. 3. The active part of the circuit contains operational amplifier OPA847 eliminating attenuation of the passive part. The complete circuit provides frequency response closed to the reversal of measured frequency response. Circuit diagram of pre-equalizer can be seen in Fig. 2. The transfer function of the pre-equalization circuit was expressed as:

$$H(j\omega) = \left(1 + \frac{R_5}{R_4}\right) \cdot \frac{R_3}{\frac{R_2}{j\omega R_2 C + 1} + R_3}, \qquad (1)$$

where ω is defined as $2\pi f$.

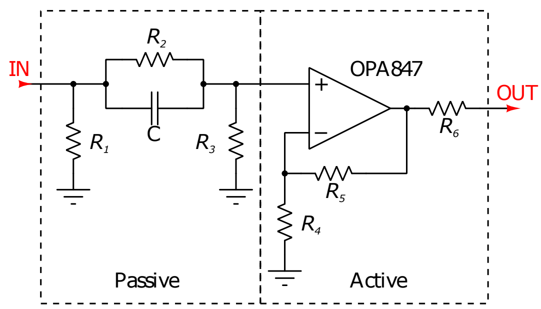

Fig. 2: Circuit diagram of active pre-equalizer with OPA847.

2.2. Simulations

Passive part of the circuit shapes the curve of frequency response and contains parallel connection of resistor R_2

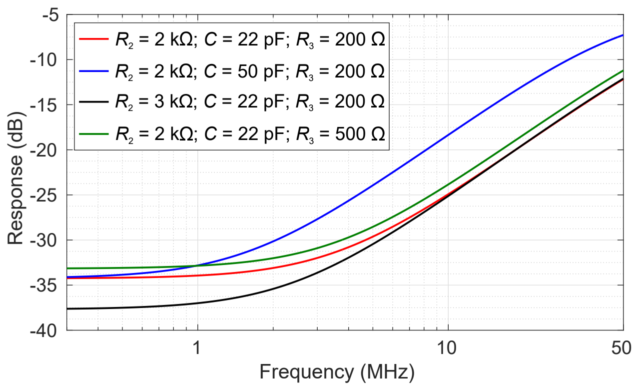

Fig. 3: Simulation results of pasive part of pre-equalizer and effect components values on frequency response.

and capacitor C and resistor R_3, parallelly connected to them. Figure 3 shows the curves from simulations, where the effect of components values on the shape of frequency response can be noticed. The best result of reversal frequency response was reached by the components $R_2 = 2$ kΩ, $C = 22$ pF and $R_3 = 200$ Ω.

Operational amplifier OPA847 was used in active part of the pre-equalization circuit. The OPA847 provides a unique combination of a very low input voltage noise, along with a very low distortion output stage to give one of the highest dynamic range of op amps available. Voltage-feedback of op amps, unlike current-feedback designs, can use a wide range of resistor's values to set up their gain. R_4 was set to 39.2 Ω and R_5 was optimized according to desired gain. Using this guideline ensures that the noise added at the output due to the Johnson noise of the resistors does not significantly increase the total noise over the 0.85 $\mathrm{V}/\sqrt{\mathrm{Hz}}$ input voltage noise for the op amp itself. This R_4 value is suggested as a good starting point for the design of the circuit.

Curves gained by simulations of different adjusted values of feedback resistor R_5 are shown in Fig. 4,

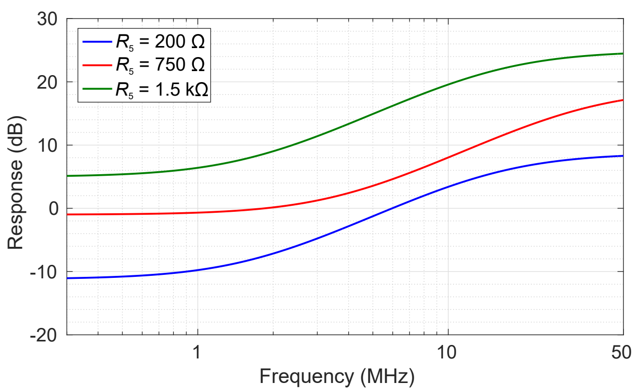

Fig. 4: Simulation results of active part of pre-equaliser and different feedback resistor values effect on frequency response.

where open-source simulation software Qucs was used. R_4 value was 39.2 Ω whereas we were trying to achieve ideal amplification for the pre-equalization circuit by adjusting value R_5. $R_5 = 750$ Ω provided the best result of reversal frequency response and achieved gain +20 V/V of operation amplifier. Values of R_4 and R_5 affected complete amplification of active part of the circuit. On the other hand, they also affected shape of the frequency response of overall pre-equalization circuit as shown in Fig. 4.

2.3. Measurement

The frequency response of constructed pre-equalizer was measured and the results were compared with simulations. Network analyzer Rhode-Schwarz ZVB 4 (3 kHz to 4 GHz) was used. Results from simulations, measurements and reverse are shown in the Fig. 5. Frequency response from simulations and measurements of the pre-equalization circuit are almost same to the reverse frequency response, which is desirable. Operational amplifier OPA847 operates up to 40 MHz as seen in Fig. 5. This is due to high amplification of OPA847, however 40 MHz is sufficient for BVL technology solution. The designed pre-equalizer circuit attenuates the input signal by about 1 dBm in the frequency range 0.2 to 2 MHz. Designed and constructed circuit achieves power level 15 dBm at 40 MHz. Bandwidth from 2 MHz to 40 MHz of designed circuit is compliant according to HomePlug AV technology solution of Broadband Power Line communication.

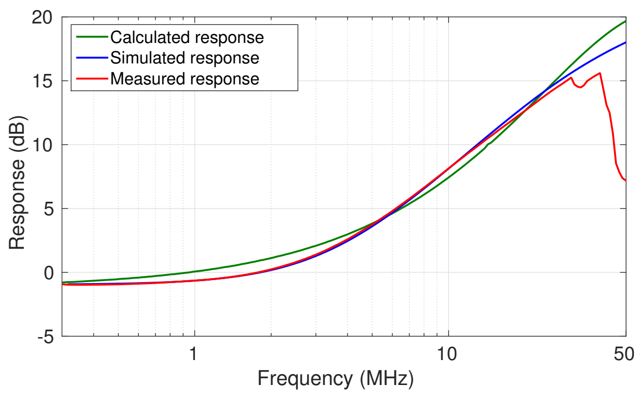

Fig. 5: Frequency response of designed circuit given by reverse, simulation and measurement.

3. Testing Effect of Pre-Equalizer on Bandwith and Modulation

To verify designed and constructed pre-equalizer effect, a new measurement was done on Philips Fortimo LED

DLM 3000 44 W/830 by aforementioned vector network analyzer. The frequency response of LED light source without designed circuit was measured at first, then with pre-equalizer. To allow determining influence of fluorescence in the phosphor, measurement was repeated without diffuser with the phosphor layer on the mentioned white light LED source. Uniform distance 40 cm between the optical transmitter and photodetector was set.

The pre-equalizer measurement results are shown in Fig. 6. It is evident how designed circuit of pre-equalizer influences frequency response of phosphor based white light and also blue part of radiation without influencing the delay due to fluorescence at phosphor layer. A bandwidth of −3 dBm was achieved at 2 MHz with white light LED without pre-equalization, whilst, a bandwidth of −10 dBm was achieved at 6 MHz. In the case of white light LED without pre-equalization, −3 dBm bandwidth was achieved at 2 MHz and −10 dBm bandwidth at 6 MHz. When with the pre-equalization circuit connected between the network analyzer and Bias-T, −3 dBm bandwidth was obtained at 3 MHz and −10 dBm bandwidth at 40 MHz. It proves how pre-equalization mitigates natural inclinations to low bandwidth of semiconductor phosphor based LED light transmitters. The bandwidth of blue part of radiation without the effect of luminescence achieved amplification by 5 dBm at 20 MHz frequency due to pre-equalization.

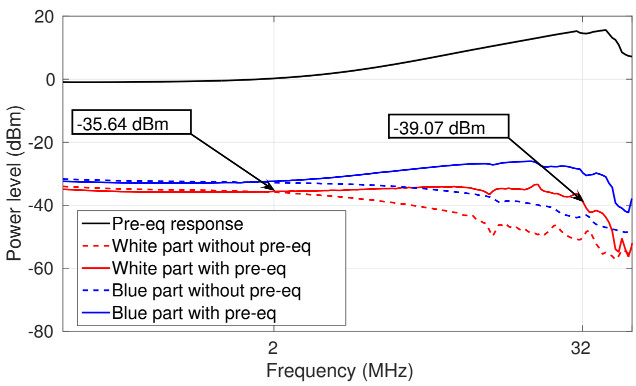

Fig. 6: Effect pre-equalizer on frequency response of white light LED and blue light LED.

The power level of the signal has higher inclination to drop toward increasing frequency, due to influence of phosphor layer. Diffuser with phosphor layer decrease power level. BVL technology with respect to HomePlug AV technology solution operates from 2 MHz to 32 MHz, hence BVL solution needs to achieve this bandwidth. An attenuation of 3.43 dBm was achieved with mentioned bandwidth due to designed pre-equalization circuit.

3.1. Experimental Setup

The block diagram for the experimental setup is shown in Fig. 7. RF VSG NI PXI-5670 (Vector signal generator) [11] was used to generate the digitally modulated signal. MQAM digital modulation was tested [10] and [14], 4QAM was used specifically.

Vector signal analyzer RF VSA NI PXI-5661 [11] was used on the receiver side. The signal modulated by a digital modulation scheme was monitored by constellation diagram and simultaneously an Error Vector Magnitude (EVM) was measured. The EVM provides a comprehensive measure of the quality of the digitally modulated signal. We used it to verify pre-equalization circuit effect on the transmitted digital signal, depending on the symbol rate (used bandwidth).

SI PIN photodetector ThorLabs PDA10A-EC is operating in the wavelength range from 200 nm to 1100 nm. Photodetector PDA10A-EC has an effective area $A_{eff} = 0.8$ mm^2 only, therefore N-BK7 Plano-Convex Lens with a focal length of 25.4 mm was used. Thanks to the lens, an adequate signal output was obtained to verify the functionality at a realistic distance of 3 m between transmitter and receiver. Center frequencies 5 MHz, 10 MHz, 15 MHz and 20 MHz were used in digital modulation scheme.

The detected signal can be represented by:

$$y(n) = g(n)x(n) + \eta(n), \tag{2}$$

where $g(n)$ and $\eta(n)$ represent the multiplicative and additive impairments to the detected signal. The multiplicative impairments can be a result of channel estimation errors or IQ imbalances, for example. The additive impairments are usually caused by thermal noise and are modeled as an *i.i.d.* (Independent and Identically Distributed random variables) complex AWGN samples with Power Spectral Density (PSD) of $N_0/2$.

EVM can be designed as the root-square (RMS) value of the difference between an array of measured symbols and ideal symbols. The EVM can be represented as:

$$EVM_{RMS} = \sqrt{\frac{\frac{1}{N}\sum_{n=1}^{N}|S_r(n) - S_t(n)|^2}{P_0}}, \tag{3}$$

where N is the number of symbols over which the value of EVM is measured. $S_r(n)$ is the normalized received n^{th} symbol which is disrupted by Gaussian noise. $S_t(n)$ is the ideal transmitted value of the n^{th} symbol $x(n)$, and P_0 is either the maximum normalized ideal symbol power or the average power of all symbols for the

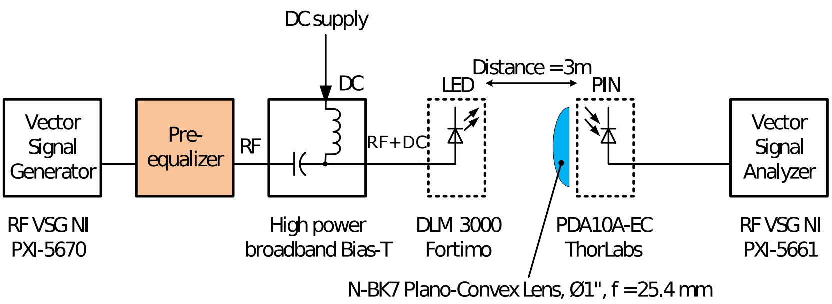

Fig. 7: Block diagram of experimental measurement.

chosen modulation. P_0 can be represented by:

$$P_0 = \frac{1}{M}\sum_{m=1}^{M}|S_m|^2. \tag{4}$$

The EVM value is normalized with average symbol energy to remove the dependency of EVM on the modulation order. Consider the detected signal in Eq. (2), where $g(n) \approx 1$. For non-data-aided receivers, the EVM is:

$$EVM_{RMS} = \sqrt{\frac{\frac{1}{N}\sum_{n=1}^{N}|y(n)-\tilde{x}(n)|^2}{P_0}}, \tag{5}$$

where $\tilde{x}(n)$ are transmitted symbols, which are estimated and used to measure the EVM value.

According to [13], the EVM for QAM signals is:

$$\begin{aligned} &EVM_{QAM} = \\ &= \left[\frac{1}{SNR} - 8\sqrt{\frac{3}{2\pi(M-1)SNR}}\sum_{i=1}^{\sqrt{M}-1}\gamma_i e^{\frac{3\beta_i^2 SNR}{2(M-1)}} \right. \\ &\left. + \frac{12}{M-1}\sum_{i=1}^{\sqrt{M}-1}\gamma_i\beta_i \operatorname{erfc}\left(\sqrt{\frac{3\beta_i^2 SNR}{2(M-1)}}\right)\right]^{1/2}, \end{aligned} \tag{6}$$

where

$$\gamma_i = 1 - \frac{i}{\sqrt{M}}, \text{ and } \beta_i = 2i - 1. \tag{7}$$

The EVM of a QAM signal in Eq. (6) can be divided into two parts. The first part is 1/SNR, which represents the ideal EVM when no errors are introduced to the symbol detection. The second part is QAM signal, which is the sum of the exponential and error function, representing the reduction in measured EVM due to the error detection.

3.2. Results and Discussions

The results were measured by the block diagram shown in Fig. 7. 4QAM digital modulation scheme was transmitted via white part of radiation with effect of the luminescence and results are shown in Fig. 8. Small differences were measured between EVM values of VLC system without the pre-equalizaion circuit and with pre-equalization for center frequency 5 MHz. The pre-equalization circuit had significant influence at higher frequencies.

Significant improvement of EVM values was verified with VLC system with pre-equalization. Most significant difference of EVM values was for center frequency of 20 MHz due to frequency response of pre-equalization circuit seen in Fig. 6. EVM value increased when symbol rate was increased, due to non-linearity of frequency spectrum.

EVM values were increased due to low signal power level and natural inclinations of the frequency response as shown in Fig. 6. Higher bandwidth was used with higher symbol rate and it increased EVM and decreased communication possibility because of inadequate frequency response. The VLC system was not suitable for use in higher central frequencies and higher bandwidth for digital modulations without pre-equalization. The VLC system with the pre-equalization circuit provided compliant conditions, thus higher central frequencies and bandwidth could be used.

4. Conclusion

In this paper pre-equalization of VLC transmitter has been presented. In order to get suitable frequency response of VLC transmitter based on phosphor white LED light source, we have been proposed equalization circuit used in our VLC system. The aforementioned HomePlug AV technology bandwidth from 2 MHz to 32 MHz was achieved with 3.43 dBm attenuation by commercial phosphorescent white light LED and proposed equalizer circuit. The objectives of this paper were to achieve suitable frequency response for the mentioned BVL technology solution. The proposed system demonstrably improves operational bandwidth in VLC system and could be considered as suitable system improvement for future Broadband over Visible Light (BVL) technology deploy.

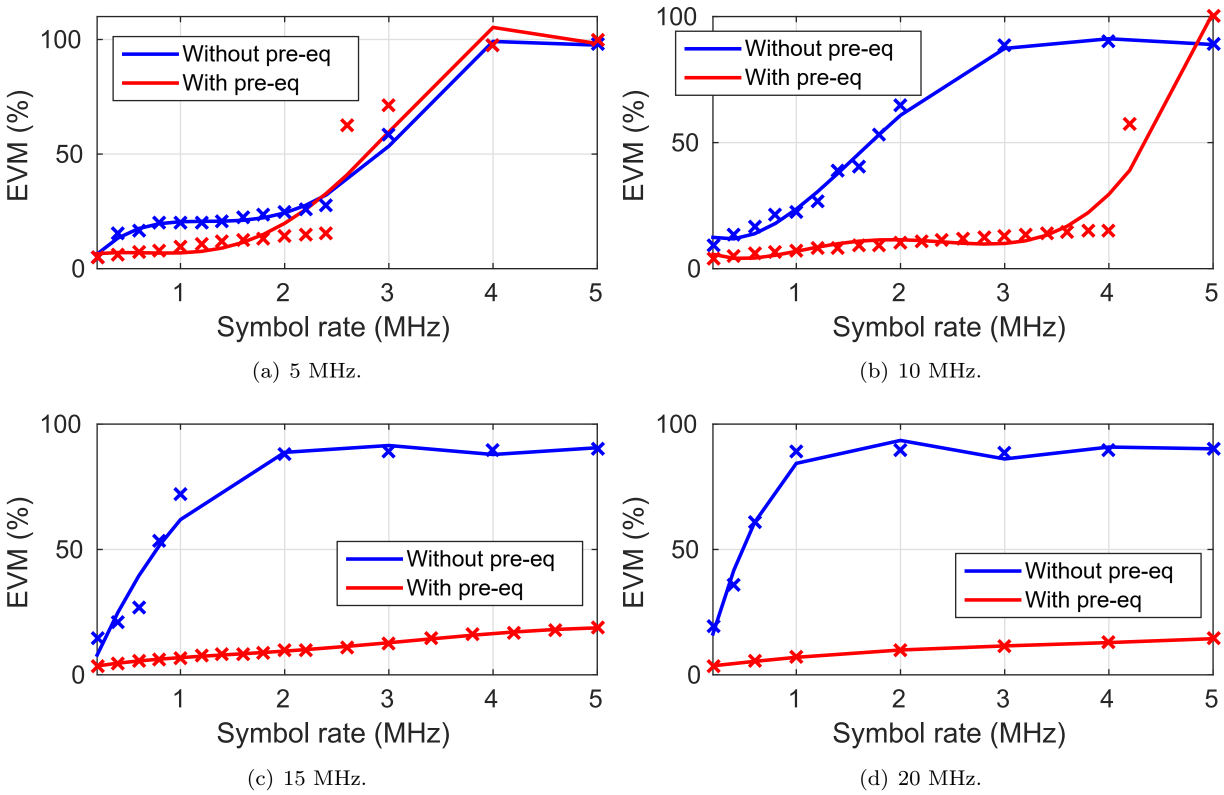

Fig. 8: Resulst of measurement EVM depending on symbol rate and carry frequency transmit 4QAM modulation via white light LED.

Acknowledgment

The research described in this article could be carried out thanks to the active support of the Ministry of Education of the Czech Republic within the projects no. SP2017/97: Remote Control of Public Lighting Luminaires via the Smart Technology Support and SP2017/128: Virtual instrumentation for the measurement and testing IV. This article was supported by projects Technology Agency of the Czech Republic TG01010137: BroadbandLIGHT. The research has been partially supported by the Ministry of Interior of the Czech Republic through grant project MVCR No. VI20172019071: Analysis of visibility of transport infrastructure for safety increasing during night, sunrise and sunset.

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About Authors

Tomas STRATIL was born in 1990 in Olomouc, Czech republic. In 2015 He received Master's degree in optical communication from VSB–Technical University of Ostrava. His research interests include Visible light communication and Smart technologies.

Petr KOUDELKA was born in 1984 in Prostejov, Czech Republic. In 2006 received Bachelor's degree on VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of telecommunications. Two years later he received on the same workplace his Master's degree in the field of Optoelectronics. In 2015 he successfully defended his dissertation thesis titled "Study of the Infoor Optical Wireless Network in the Visible Optical Radiation". He works as an Asistant Professor at VSB–Technical University of Ostrava since 2016. His current research interests include Wireless Optical Communications, Optical Access Networks and Smart City technologies.

Radek MARTINEK was born in 1984 in Czech Republic. In 2009 he received Master's degree in Information and Communication Technology from VSB–Technical University of Ostrava. Since 2012 he worked here as a Research Fellow. In 2014 he successfully defended his dissertation thesis titled „The Use of Complex Adaptive Methods of Signal Processing for Refining the Diagnostic Quality of the Abdominal Fetal Electrocardiogram". He became an Associate Professor in Technical Cybernetics in 2017 after defending the habilitation thesis titled "Design and Optimization of Adaptive Systems for Applications of Technical Cybernetics and Biomedical Engineering Based on Virtual Instrumentation". He works as an Associate Professor at VSB–Technical University of Ostrava since 2017. His current research interests include: Digital Signal Processing (Linear and Adaptive Filtering, Soft Computing - Artificial Intelligence and Adaptive Fuzzy Systems, Non-Adaptive Methods, Biological Signal Processing, Digital Processing of Speech Signals); Wireless Communications (Software-Defined Radio); Power Quality Improvement. He has more than 70 journal and conference articles in his research areas.

Tomas NOVAK was born in 1972 in Pribram, Czech Republic. In 1996 received Master's degree on VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Electrical Engineering. Seven years later he received on the same workplace his Ph.D. degree in the field of Electric Light and Diagnostic. Now he works as an Associate Professor at the same university. His current research interests include Public Lighting, Lighting Pollutions, Interior Light Controlling and Smart City technologies.