Purposeful Suppression and Reconstruction of White Light from LED for Improvement of Communication Properties

Jan VITASEK, Jan LATAL, Tomas STRATIL, Stanislav HEJDUK, Ales VANDERKA, Lukas HAJEK, Jakub KOLAR

Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, 17. listopadu 15, 708 00 Ostrava, Czech Republic

jan.vitasek@vsb.cz, jan.latal@vsb.cz, tomas.stratil@vsb.cz, stanislav.hejduk@vsb.cz, ales.vanderka@vsb.cz, lukas.hajek@vsb.cz, jakub.kolar.st@vsb.cz

DOI: 10.15598/aeee.v17i1.2671

Abstract. *Visible Light Communication (VLC) technology uses white Light Emitting Diodes (LED) for providing illumination and communication at the same time. White LEDs have excellent illumination properties but their communication properties need improvement. This article proposes a way how to evade the communication limitations of white LEDs. A part of original white LED spectrum is suppressed by an optical filter. Then the suppressed part is replaced by another LED. The correct choice of suitable LED enables to reconstruct the original spectrum. This solution removes the limitations because the white LED emits continuously. Data are carried by the communication LED only. The evaluation of reconstruction of original white light is measurement of the colour coordinates x and y. Furthermore, the communication properties of this transmitter were tested and obtained results are shown in this paper. EVM parameter was measured.*

Keywords

CIE coordinates, communication via LEDs, EVM, MQAM, VLC, white light.

1. Introduction

One of research directions in optical communications is the Visible Light Communication (VLC). The VLC technology joins together two functions, communication and illumination [1], [2], [3], [4] and [5]. The VLC is mainly used indoor and it has the potential to partially replace the radiofrequency communication (Wi-Fi). This replacement is caused by several factors [6]:

- Dwindling RF spectrum: the radiofrequency spectrum is limited, its usage is regulated due to interferences, pollution and efficient spectral usage. It is cheaper for mobile operators to buy spectrum than building more base stations for capacity increasing. Moreover, it reduces the chance for future operators to enter the market. The requirements for wireless data transmission are constantly increasing, therefore the radio frequency spectrum becomes congested. There have been developments to use the Terahertz frequency range between the RF and microwave spectrum, but it would mean creating an entirely new class of infrastructure compatible with the wavelength band. On the other hand, visible light has 10 000 times greater spectrum than radio waves [7] and [8].

- Capacity: Mobile data will grow 6.3 times between 2013 and 2018 and the growth will be strongest outside Europe and North America [9] and [10]. Thanks to the massive increase in data usage, mobile operators focus on public Wireless Fidelity (Wi-Fi) and other alternative technologies. The growth of mobile data usage is obvious.

- Interference: VLC is safe and does not cause any interference with RF waves. Thus this technology is perfectly suitable for communication in hospital, industrial and aerospace applications [11].

- Security: RF waves pass through walls and could be received by a third person, are susceptible to snooping. Light has clearly defined boundaries and defined coverage zones with enhanced security for VLC.

- Safety: in illumination conditions, there are no health hazards of visible light. Visible light satisfies the eye-and-skin safety regulations [12].
- Energy efficiency: LEDs are energy efficient and highly controllable light sources, allowing them to be a part of Green technology. LEDs roughly use one twentieth of energy of a conventional light source. If all conventional light sources are replaced by LEDs, the global energy consumption would reduce by as much as 50 %, and the CO_2 emissions will also reduce [13].
- Easy implementation into existing infrastructure: VLC can be easily implemented into existing lighting infrastructure with the addition of a few relatively simple and cheap front end components [14] and [15].
- Low cost: another advantage of VLC devices is their comparably low cost. The RF links operating over approximately 10 m provide data rates of up to 1 $Mb \cdot s^{-1}$ in the 2.4 GHz band for a cost of nearly US $5. VLC links can transmit at 4 $Mb \cdot s^{-1}$ over short distances using optoelectronic devices which cost approximately US $1 [16] and [17].

LEDs have many advantages in comparison to conventional illumination sources (light bulbs and fluorescent lamps). LEDs can be switched on and off instantly. The instant on and off switching is essential for providing communication [3]. The other advantages of LEDs are higher efficiency, longer lifetime, higher tolerance to humidity, smaller and compact size, minimum heat generation compared to the conventional illumination sources, and lower power consumption. LEDs are more ecological because they are mercury free [4], [5], [18] and [19]. The key element of the VLC is a white Light Emitting Diode (LED).

LEDs provide above-described advantages, but there are also several obstructions, mainly in the communication domain. White LEDs are based on two principles [3]. The first principle uses three chips emitting blue, green and red light. If these chips are correctly power supplied, they create white light together. This principle is called colour mixing. The other principle is based on the conversion of the emitted wavelength to another wavelength. The converters are luminophores which convert blue light to yellow. The most often used luminophores are Yttrium Aluminium Garnets ($Y_3Al_5O_{12}$). The basis is the blue light emitting chip. This blue light excites the luminophore layer and a part of blue light is converted to yellow light. The rest of the blue light and the yellow light create the white light together. Both of these methods have their limitations. The three-colour LEDs are power supplied by high current, therefore, the fast on and off switching is problematic. Whereas the LEDs with the luminophore suffer the luminescence delay. After switching off of the exciting blue light, the luminophore still emits yellow light for some time, which extends the symbol duration time. This delay is called the luminescence decay [20], [21], [22], [23] and [24].

2. Solution of White LEDs Obstructions

This article proposes a solution that overcomes both above-described obstructions. The basis is a purposeful suppression of a part of the spectrum emitted by the white LED by using a suitable optical filter. The suppressed part is then replaced by spectral and intensity suitable LED. Both these LEDs then create the original white light.

The advantage is that the white LED emits continuously, it is not switched on and off. Also, the high forward current is not switched. There is even no luminophore decay. This LED is called as the illumination LED. Only the LED which replaces the suppressed part of the spectrum is switched on and off. The switched LED is a monochromatic LED which is supplied by lower forward current and creation of light is given only by features of semiconductor material. This LED is called the communication LED.

3. Measurement of Illumination Properties

We needed several components to realize the measurement. The basis was the white power LED. The forward current of this power LED was 700 mA. Further, a notch filter was placed to this white power LED. The notch filter suppressed a part of LEDs spectrum. The next used element was a suitable chosen communication LED. The communication LED had to fulfil the spectral properties for replacing the suppressed part. Before measurement of illumination properties, we looked for suitable LEDs (according to the spectrum) and we measured them. According to this, we choose the most suitable LED. Further, we solved the problem how to merge two light beams from the two LEDs in one. For this purpose, we used a beamsplitter 50:50. The disadvantage of this beamsplitter is that half of the optical power is waste. This waste is unallowable therefore a mirror was also used. Moreover, a diffuser was at the end for better mixing of LEDs beams. The final arrangement is shown in Fig. 1.

The white LED was supplied by constant forward current 700 mA. The forward current of the communication LED was gradually increased with the step of

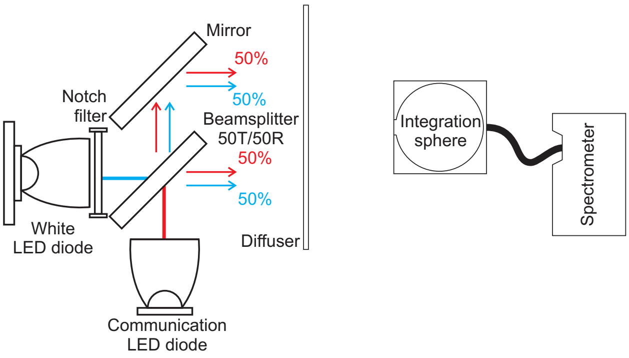


Fig. 1: Arrangement of illumination measurement.

10 mA. The aim was to find the specific forward current of the communication LED when the difference between colour coordinates x and y in CIE diagram was the smallest before and after reconstruction.

3.1. Measurement Procedure

A spectrometer with an integration sphere was used for measurement. At first, we measured the spectrum of the white power LED, Fig. 2. Furthermore, the colour coordinates and Correlated Colour Temperature (CCT) were noted. Then we put the notch filter to the white LED. The transmission of this filter is seen in Fig. 3. Thereby a part of the spectrum was suppressed. The communication LED began to emit light with the forward current 100 mA. After this setting, we measured the compound spectrum, colour coordinates x and y, and also the CCT. Then the forward current was increased with the step of 10 mA and the measurement was repeated. This procedure was done up to maximal value 350 mA of the forward current of the communication LED.

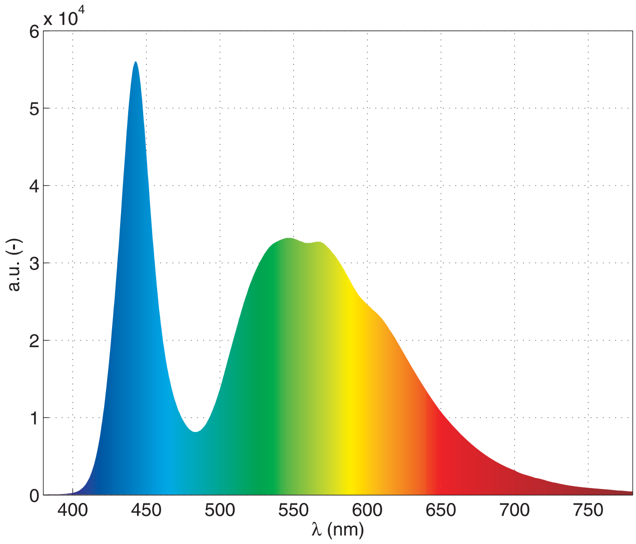


Fig. 2: White LED spectrum.

3.2. Measurement Results

The colour coordinates of original white light were $x = 0.3064$ and $y = 0.3107$, the CCT was 7070.7 K. The best reconstruction of white light came for the forward current of the communication LED 280 mA, see Fig. 4. The colour coordinates of the compound spectrum were $x = 0.3087$ and $y = 0.3108$, CCT = 6915.7 K. These measured values could be compared according to the relation, which is derived from relative error:

$$\delta(\%) = \frac{x_{rec} - x_{org}}{x_{org}} \cdot 100, \qquad (1)$$

where index *rec* means the reconstructed value and *org* is the original value. According to the Eq. (1) the colour coordinates changed less than 1 %. The CCT changed by 2.2 %. The reconstruction was very suc-

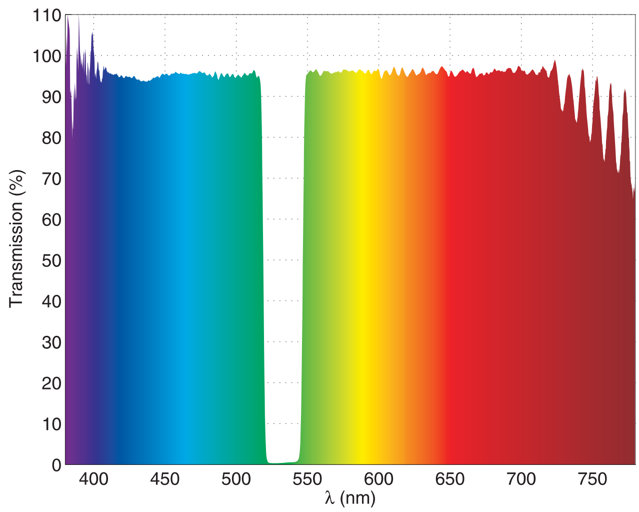


Fig. 3: Notch filter spectrum.

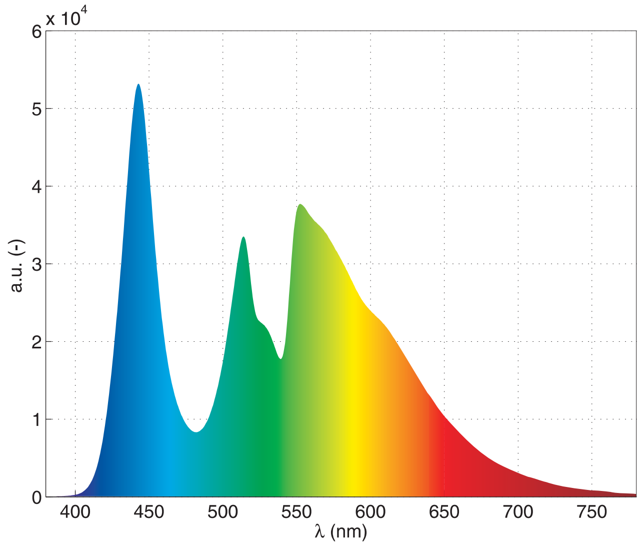


Fig. 4: Reconstructed spectrum.

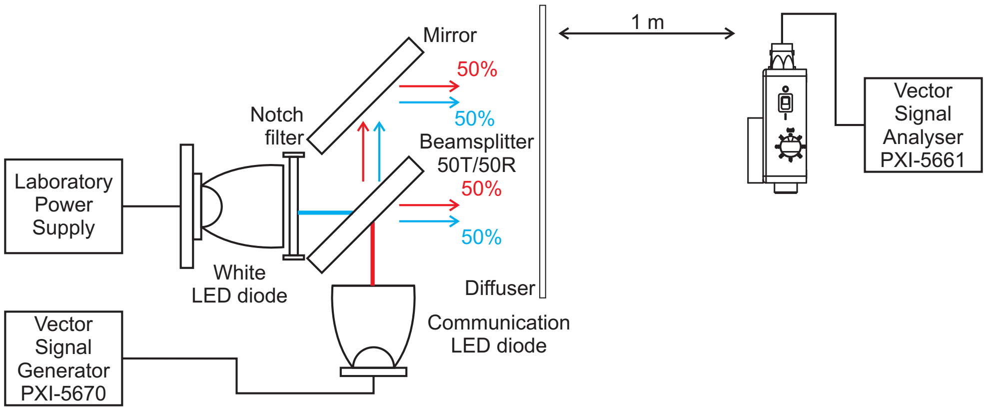


Fig. 5: Measurement of communication properties.

cessful, the measured values could be not recognized by human eye.

4. Measurement of Communication Properties

The next step was to test the communication properties of the constructed transmitter with compound spectra. The measurement was done with several pieces of equipment and instruments which are shown in Fig. 5. The Vector Signal Generator PXI-5670 created a pseudorandom sequence. This generator can create different modulation formats. A signal from PXI-5670 generator was connected to the communication LED. The illumination LED was supplied by the Laboratory Power Supply. The distance between the transmitter and the receiver was 1 m. On the receiver side, there was a PIN photodetector PDA10A-EC, its output signal was connected to the Vector Signal Analyser PXI-5661. The Analyser PXI-5661 demodulated the received signal and measured the EVM parameter. Vector Signal Generator and Analyser were connected together.

For the present, two modulation formats 4QAM and 8QAM were tested. The carrier frequencies 3 MHz and 4 MHz were set for both modulations. The changing parameter was symbol rate which was gradually increased up to communication break up. The bitrate could be calculated from the symbol rate by the help of Hartley law [25]:

$$R = f_s \cdot \log_2 M, \quad (2)$$

where R is the bitrate, f_s is the symbol rate and M is number of states, $M = 4$ for 4QAM and $M = 8$ for 8QAM. The Vector Signal Analyser PXI-5661 showed results as EVM (Error Vector Magnitude) parameter.

4.1. Error Vector Magnitude

Error Vector Magnitude (EVM) is a measurement of demodulator performance in the presence of impairments. The measured symbol location obtained after decimating the recovered waveform at the demodulator output is compared against the ideal symbol locations. The Root-Mean-Square (RMS) EVM and phase error are then used in determining the EVM measurement over a window of N demodulated symbols [26]:

$$EVM = \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[\left(I_j - \widetilde{I}_j\right)^2 + \left(Q_j - \widetilde{Q}_j\right)^2\right]}}{|\vec{v}|}, \quad (3)$$

where I_j is the I component of the j^{th} symbol received, Q_j is the Q component of the j^{th} symbol received, $\widetilde{I}_j$ is the ideal I component of the j^{th} symbol received and $\widetilde{Q}_j$ is the ideal Q component of the j^{th} symbol received, $\vec{v}$ is the ideal symbol vector. The result is expressed in percentage [26]. The EVM provides a comprehensive measure of the quality of the digitally modulated signal.

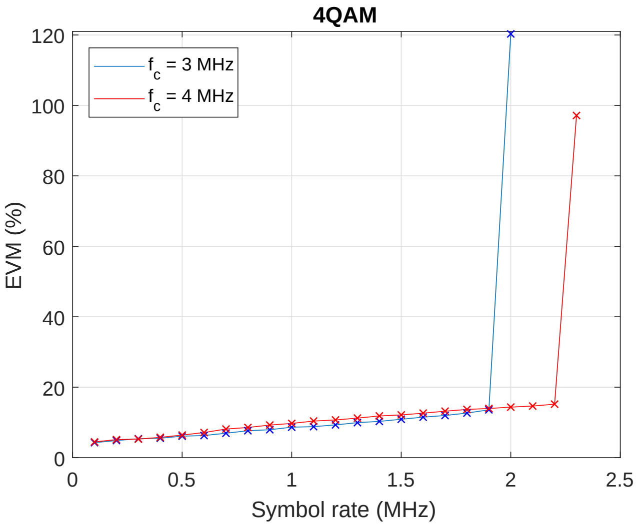
According to [27], the EVM for QAM signals is:

$$EVM_{QAM} = \left[\frac{1}{SNR} - 8\sqrt{\frac{3}{2\pi(M-1)SNR}}\sum_{i=1}^{\sqrt{M}-1}\gamma_i e^{\frac{3\beta_i^2 SNR}{2(M-1)}} + \frac{12}{M-1}\sum_{i=1}^{\sqrt{M}-1}\gamma_i\beta_i \mathrm{erfc}\left(\sqrt{\frac{3\beta_i^2 SNR}{2(M-1)}}\right)\right]^{1/2}, \quad (4)$$

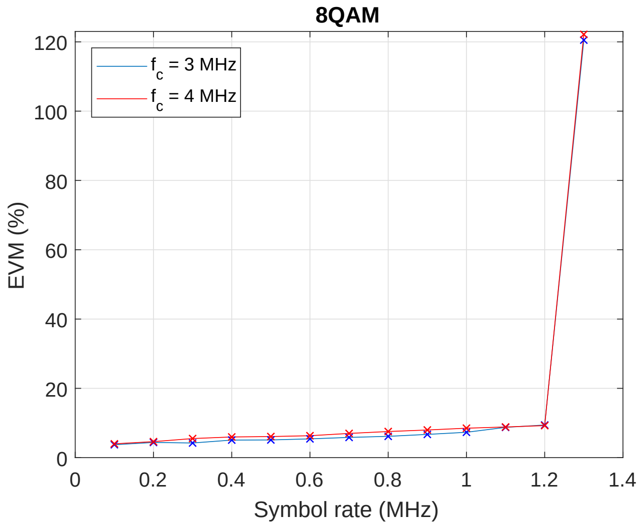
where $\gamma_i = 1 - \frac{i}{\sqrt{M}}$ and $\beta_i = 2i - 1$.

4.2. Measurement Results

The measured results are summarized in Fig. 6. For the end user, the most interesting is the bitrate which was calculated according to the Eq. (2). Modulation 4QAM



(a) 4QAM.



(b) 8QAM.

Fig. 6: EVM results.

with carrier frequency $f_c = 3$ MHz reached the bitrate 3.8 Mb·s^{-1}, after that, the communication broke. Modulation 4QAM with carrier frequency $f_c = 4$ MHz reached the bitrate 4.4 Mb·s^{-1}. Modulation 8QAM with carrier frequency $f_c = 3$ MHz reached the bitrate 3.6 Mb·s^{-1}. Modulation 8QAM with carrier frequency $f_c = 4$ MHz also reached the bitrate 3.6 Mb·s^{-1} before communication break up.

5. Conclusion

This paper proposes one of the possibilities how to remove the problem with the communication properties of the white LEDs for VLC. The measured results showed that the reconstruction of the original spectrum is possible and it was very successful. The colour coordinates almost did not change, the CCT changed slightly. The differences are not recognizable by the human eye. Furthermore, the communication properties of the transmitter with suppressed and reconstructed spectrum were tested. Two modulation formats 4QAM and 8QAM were used for testing, each modulation had carrier frequencies 3 MHz and 4 MHz. The comparison of results shows that the greatest bitrate was reached with 4QAM modulation and carrier frequency 4 MHz, namely 4.4 Mb·s^{-1}. The modulation 8QAM with both carrier frequencies obtained the same results that were even worse than 4QAM modulation. The distance between the transmitter and the photodetector was only 1 m. The reason for this short distance is, above all, using the diffuser which has relative great attenuation. The solution of this problem is geometry improvement of the proposed transmitter.

Acknowledgment

The authors would like to acknowledge the financial support of the Ministry of Education, Youth and Sports of the Czech Republic under Projects No. SP2019/80 and SP2019/143 of VSB–Technical University of Ostrava, Czech Republic. Our research was also supported by Projects No. VI20172019071, VI20152020008, TA04021263, TK01020162 and TK01020178. The work has been partially supported by Project No. CZ.1.07/2.3.00/20.0217.

References

[1] CHEN, Y. C., S. S. WEN, Y. X. WU, Y. Y. REN, W. P. GUAN and Y. L. ZHOU. Long-range visible light communication system based on LED collimating lens. *Optics Communications*. 2016, vol. 377, iss. 1, pp. 83–88. ISSN 0030-4018. DOI: 10.1016/j.optcom.2016.05.036.

[2] NOVAK, T., B. SOCHA, Z. CARBOL and K. SOKANSKY. Luminance evaluation of LED indoor luminaires for workspaces lighting. In: *Proceedings of the 13th International Scientific Conference Electric Power Engineering 2012*. Ostrava: VSB–TUO, 2012, pp. 1185–1188. ISBN 978-80-214-4514-7.

[3] E. F. SCHUBERT. *Light-Emitting Diodes*. 2$^{\text{nd}}$ ed. Cambridge: Cambridge University Press, 2006. ISBN 978-0-521-86538-8.

[4] MINH, T. H. Q., N. H. K. NHAN, T. P. VO and N. D. Q. ANH. Enhancement of Color Rendering Index for White Light LED Lamps by Red Y_2O_3:EU^{3+} Phosphor. *Advances in Electrical and Electronic Engineering*. 2016, vol. 14, no. 3, pp. 340–344. ISSN 1804-3119. DOI: 10.15598/aeee.v14i3.1642.

[5] MARE, R. M., C. E. CUGNASCA, C. L. MARTE and G. GENTILE. Intelligent transport systems and visible light communication applications: An overview. In: *IEEE Conference on Intelligent Transportation Systems*. Rio de Janeiro: IEEE, 2016, pp. 2101–2106. ISBN 978-1-5090-1889-5. DOI: 10.1109/ITSC.2016.7795896.

[6] KARUNATILAKA, D., F. ZAFAR, V. KALAVALLY and R. PARTHIBAN. LED Based Indoor Visible Light Communications: State of the Art. *IEEE Communications Surveys & Tutorials*. 2015, vol. 17, iss. 3, pp. 1649–1678. ISSN 1553-877x. DOI: 10.1109/COMST.2015.2417576.

[7] OH, M. A flicker mitigation modulation scheme for visible light communications. In: *International Conference on Advanced Communication Technology (ICACT)*. PyeongChang: IEEE, 2013, pp. 933–936. ISBN 978-1-4673-3148-7.

[8] HOSAKO, I., N. SEKINE, M. PATRASHIN. At the Dawn of a New Era in Terahertz Technology. *Proceedings of the IEEE*. 2007, vol. 95, iss. 8, pp. 1611–1623. ISSN 0018-9219. DOI: 10.1109/JPROC.2007.898844.

[9] WOOD, R. Wireless network traffic worldwide: forecasts and analysis 2014–2019: Research Forecast Report. *Analysys Mason* [online]. 2014. Available at: `www.analysysmason.com`.

[10] KIM, S.-M. and S.-M. KIM. Performance improvement of visible light communications using optical beamforming. In: *Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*. Da Nang: IEEE, 2013, pp. 362–365. ISBN 978-1-4673-5990-0. DOI: 10.1109/ICUFN.2013.6614842.

[11] MA, H., L. LAMPE a S. HRANILOVIC. Integration of indoor visible light and power line communication systems. In: *2013 IEEE 17th International Symposium on Power Line Communications and Its Applications*. Johannesburg: IEEE, 2013, pp. 291–296. ISBN 978-1-4673-6016-6. DOI: 10.1109/ISPLC.2013.6525866.

[12] WANG, Y., Y. WANG, N. CHI, J. YU and H. SHANG. Demonstration of 575-Mb/s downlink and 225-Mb/s uplink bi-directional SCM-WDM visible light communication using RGB LED and phosphor-based LED. *Optics Express*. 2013, vol. 21, iss. 1, pp. 1203–1208. ISSN 1094-4087. DOI: 10.1364/OE.21.001203.

[13] KAVEHRAD, M. Sustainable energy-efficient wireless applications using light. *IEEE Communications Magazine*. 2010, vol. 48, iss. 12, pp. 66–73. ISSN 0163-6804. DOI: 10.1109/MCOM.2010.5673074.

[14] JOVICIC, A., J. LI and T. RICHARDSON. Visible light communication: opportunities, challenges and the path to market. *IEEE Communications Magazine*. 2013, vol. 51, iss. 12, pp. 26–32. ISSN 0163-6804. DOI: 10.1109/MCOM.2013.6685754.

[15] O'BRIEN, D. C. Visible Light Communications: Challenges and potential. In: *IEEE Photonic Society 24th Annual Meeting*. Arlington: IEEE, 2011, pp. 365–366. ISBN 978-1-4244-8939-8. DOI: 10.1109/PHO.2011.6110579.

[16] RAMIREZ-INIGUEZ, R., S. M. IDRUS and Z. SUN. *Optical wireless communications: IR for wireless connectivity*. New York: CRC Press, 2007. ISBN 0-8493-7209-7.

[17] *Infrared Data Association* [online]. 2012. Available at: `http://www.irda.org/`.

[18] LINER, A., M. PAPES, J. JAROS, F. PERECAR, L. HAJEK, J. LATAL, P. KOUDELKA and V. VASINEK. Software Design of SMD LEDs for Homogeneous Distribution of Irradiation in the Model of Dark Room. *Advances in Electrical and Electronic Engineering*. 2015, vol. 12, no. 6, pp. 622–630. ISSN 1804-3119. DOI: 10.15598/aeee.v12i6.1297.

[19] STRATIL, T., P. KOUDELKA, R. MARTINEK and T. NOVAK. Active Pre-Equalizer for Broadband over Visible Light. *Advances in Electrical and Electronic Engineering*. 2017, vol. 15, no. 3, pp. 553–560. ISSN 1804-3119. DOI: 10.15598/aeee.v15i3.2210.

[20] CHEN, J., W. CRANTON and M. FIHN. *Handbook of visual display technology*. New York: Springer, 2012. ISBN 978-3-540-79566-7.

[21] WANG, Y., T. LAN and G. NI. Optical receiving system based on a compound parabolic concentrator and a hemispherical lens for visible light communication. *Applied Optics*. 2016, vol. 55, iss. 36, pp. 10229–10238. ISSN 0003-6935. DOI: 10.1364/AO.55.010229.

[22] FALL, M., G. YAN and Z. ZHONG. Visible Light Communication System Based on

Hadamard Coded 64/QAM-OFDM Signal. *International Journal of Future Generation Communication and Networking*. 2017, vol. 10, iss. 4, pp. 61–70. ISSN 2233-7857.

[23] HONG, Y., J. XU and L.-K. CHEN. Experimental investigation of multi-band OCT precoding for OFDM-based visible light communications. *Optics Express*. 2017, vol. 25, iss. 11, pp. 12908–12914. ISSN 1094-4087. DOI: 10.1364/OE.25.012908.

[24] KHALLAF, H. S., A. S. GHAZY, H. M. H. SHALABY and S. S. A. OBAYYA. Performance analysis of visible light communication systems over fading channels. In: *19th International Conference on Transparent Optical Networks (ICTON)*. Girona: IEEE, 2017, pp. 1–4. ISBN 978-1-5386-0859-3. DOI: 10.1109/ICTON.2017.8024762.

[25] HARTLEY, R. V. L. Transmission of Information. *Bell System Technical Journal*. 1928, vol. 7, iss. 3, pp. 535–563. ISSN 0005-8580. DOI: 10.1002/j.1538-7305.1928.tb01236.x.

[26] Modulation Error Ratio (MER) and Error Vector Magnitude (EVM). *National Instrument* [online]. 2014. Available at: `http://www.ni.com/white-paper/3652/en/`.

[27] MAHMOUD, H. A. and H. ARSLAN. Error vector magnitude to SNR conversion for nondata-aided receivers. *IEEE Transactions on Wireless Communications*. 2009, vol. 8, iss. 5, pp. 2694–2704. ISSN 1536-1276. DOI: 10.1109/TWC.2009.080862.

About Authors

Jan VITASEK was born in Opava, Czech Republic. In 2009 he finished M.Sc. study at Brno University of Technology, Faculty of Electrical Engineering and Communication. In 2014 he finished Ph.D. study at Department of Telecommunications, VSB–Technical University of Ostrava. His interests are Free Space Optics, indoor Free Space Optics networks and visible light communication. He is engaged in project dealing with VLC.

Jan LATAL was born in Prostejov, Czech Republic. In 2006 he was awarded his B.Sc. degree and in 2008 M.Sc. degree at VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications in 2008. He defended his Ph.D. thesis in 2015, and he works in the field of Wireless Optical Communications, Optical Communications and Distributed Temperature Sensing Systems.

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.

Stanislav HEJDUK was born in Ostrava, Czech Republic, in November 1985. He received his M.Sc. degree in telecommunication technologies from VSB–Technical University of Ostrava, in 2010. In 2017 he finished Ph.D. study at Department of Telecommunications, VSB–Technical University of Ostrava. His research focuses on transmitters for Mobile Free-Space Optical Communications.

Ales VANDERKA was born in 1988 in Vitkov, Czech Republic. He finished M.Sc. study at the VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications in 2013. In present time he is Ph.D. student at VSB–Technical University of Ostrava. He focuses on optical technologies and especially Free Space Optic.

Lukas HAJEK was born in 1989 in Bohumin, Czech Republic. In 2013 he finished M.Sc. study at VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications. In present time he is Ph.D. student at VSB–Technical University of Ostrava. His interests are Free Space Optics and aging of optical communication components.

Jakub KOLAR is currently a Ph.D. student with the Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava.