Special issue of the 2nd International Conference on Computational and Experimental Science and Engineering (ICCESEN 2015)

2 × 2 MIMO VLC Optical Transmission System Based on LEDs in a Double Role

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The article presents the concept solution of two main issues of visible light communication systems, i.e. the lack of a cost-effective feedback channel and the handling of high throughput. The concept is based on merging of the multiple input multiple output approach, well-known from radio transmission domain, with using of LEDs in a double role, i.e. both as emitters and detectors of light. The feasibility of the proposal was confirmed by the results of the research, carried out for two-channel system of this type.

DOI: 10.12693/APhysPolA.130.41

PACS/topics: 07.50.Qx, 07.60.–j, 42.72.Bj, 42.79.–e, 42.82

1. Introduction

Forecast of changes in the lighting market, which are being the consequence of the introduction of new directives and regulations issued by the European Union in a few recent years [1, 2], indicates that by the year of 2020 this market will be totally dominated by the light emitting diode (LED) devices, which offer a lot of advantages compared to conventional light bulbs [3]. Rapid growth of the share of LED devices in the lighting market creates among others the possibilities of development of a novel type of wireless transmission systems, better known as the visible light communication (VLC) systems [4–13], which are based on using of the lighting light as a transmission medium. It is almost sure that in the near future such approach has a chance to play an important role in the context of access systems, however some issues related to it have to be solved first. By this we mean the assurance of effective and low-cost feedback channel for transmission from the receiver to the transmitter and achievement of an appropriate rate of transmission. The feasibility of application the multiple input multiple output (MIMO) schema, which is a well-known technique from the radio transmission domain, in such systems was introduced for the first time in [14]. In [15] the MIMO approach has been considered, by theoretical evaluation of performance for different modulation schemes, under the hypotheses of alignment and nonalignment between LEDs and photodiodes. Moreover, the promising experimental results were reported in [16–18], regarding the usability of the MIMO technique in the VLC systems. It is known that by the application of MIMO technique it is possible to improve the transmission quality due to spatial diversity or to increase system throughput by using of multiplexing approach. This means for us that by application of MIMO technique we can ensure appropriate level of the bitrate in the VLC systems. However, the problem with the assurance of an appropriate feedback channel remains still unsolved. Therefore we were focusing on this issue in this work. The results of research reported in [18–20] prove that some of LEDs, especially the high brightness LEDs (HBLEDs), can be used successfully as photodetectors in the VLC systems, if they are polarised in an appropriate fashion. The paper postulates a merge of both those approaches, which can be considered as a potential solution for the drawbacks indicated above. The rest of the article is focused on presentation of experimental results obtained regarding a two-channel (2 × 2) MIMO-VLC system, the construction of which was based on utilization of only LEDs (red, one-colour HBLEDs were used), which were used both as emitters and as light detectors as well. The presentation of results is preceded by the explanation of the concept of the optical MIMO system. Among others an appropriate theoretical model is briefly presented.

2. Optical MIMO transmission theory

The approach based on using of the MIMO technique, regarding wireless communications, means that data are transmitted in a form of more than one stream, in such a way that many paths of transmission are constituted at the same time, between multiple transmitting antennas and multiple receiving antennas [15, 16]. Of course, when we talk about a realization of the MIMO transmission in the optical domain, we are thinking rather about many light emitters and detectors instead of the radio antennas. Nevertheless the principal idea is maintained. If we are talking about indoor VLC systems, where the LED light bulbs, used as light sources, are constituted typically of many separate LEDs. Theoretically, a separation of individual data transmitters is possible both on the level of whole light bulbs, if more than one is installed in the same site, as well as on the level of individual LEDs or their groups inside of a single light bulb. Regardless, which scenario is realized in practice, an action of the optical MIMO-VLC system can be described by a mathematical model, graphical interpretation of which is depicted

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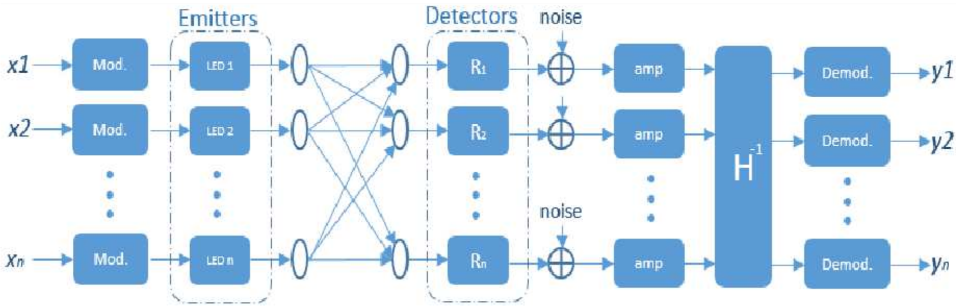

Fig. 1. Model of optical MIMO communication system.

in Fig. 1. In such transmission system the signals are transmitted simultaneously by N transmitters and are received by M receivers, where $(M \geq N)$. Its action can be described by a vector equation as follows:

$$X = HY + n, \quad (1)$$

where X is the vector of transmitted signals, Y is the vector of received signals, H stands for channel transfer matrix.

This matrix is formed by the transmittance between each transmitter and each receiver, and can be estimated by the gain between the ith receiver and the jth transmitter. More detailed analysis on this topic can be found among others in [14, 15]. It is quite clear that by inverting the matrix H we can recover the original signals, according to formula:

$$Y = H^{-1}X + n. \quad (2)$$

Obviously, the matrix H may not be singular and its numerical conditioning determines the values of the channel SNR [21]. The matrix H^{-1} may be found by some optimization algorithms or calculated at the system initialization stage. In practice, the last method is mostly used. Because in the process of recovering signals on the receiver side, the knowledge about the inverse matrix H^{-1} is necessary, the greater part of such systems work in two phases. In the first one (the initialization mode), the matrix H is determined; typically, for this purpose, some special pilot signals are transmitted. Based on it, the matrix H^{-1} is then calculated. In the second stage (the working mode), information signals are send. The inverse matrix H^{-1} is used in the process of the recovery of the originally transmitted signals.

3. Experiment

The postulated approach, which uses the MIMO technique with simultaneous application of the LEDs in a double role, as a part of the VLC system, was tested using the experimental setup, the scheme of which is shown in Fig. 2.

Two red LEDs (C503B-RAN; Cree) were modulated by pseudorandom sequences of a length 2^9-1 in a format of non return to zero (NRZ) with a 10 Mps bitrate, originating from the arbitrary waveform generator (AWG-Tektronix 7122C). The diodes were spaced apart by 4 cm. The bias current (20 mA) was typical for these LEDs, and the modulation index was set so that there was no

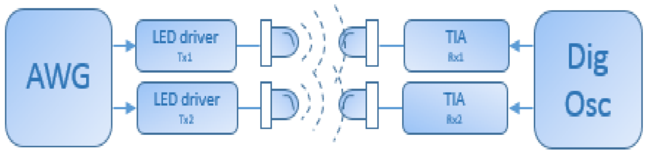

Fig. 2. Scheme of experimental setup.

signal clipping. At the receiver side the LEDs operating as photo-detectors by application of reverse bias (−30 V) were connected to trans-impedance amplifiers (TIA). Application of the −30 V reverse bias ensured that absolute responsivities of used LEDs were higher than 0.12 A/W. Next, the signals from the TIAs were fed to a digital oscilloscope (Agilent DSO6401S), where they were sampled and recorded for the purpose of their further digital processing, which was realized in the Matlab environment. The investigations were carried out in the scenario, which has consisted of two phases. In the first phase, at both channels the established training sequences were transmitted separately. This step had a crucial importance for determination of the H-matrix elements. While in the second phase the real MIMO transmission (both channels were transmitted simultaneously) was carried out. The inter-channel crosstalk elimination was implemented using of the Matlab software. Zero forcing (ZF) algorithm, which is based on the knowledge about inverse matrix H^{-1}, was applied for this purpose. Reception of transmitted signals without application of any off-line crosstalk elimination was also performed for all recorded sets for comparison. The procedure was repeated each time for each realization. In order to assess the quality of transmission for each realization the eye diagrams were constructed in the offline mode. Based on them the Q parameters were estimated.

3.1. Results

Results obtained during the experiment, where the distance between two transmitting diodes and two receiving diodes was changed between 0 (back to back) and 25 cm, while maintaining a fixed position of them relative to each other, are depicted in Fig. 3.

It can be easily seen that the quality of the MIMO LED-LED VLC transmissions, both for a transmission with elimination of crosstalk as well as without it, in case of realizations where the distance between transmitters

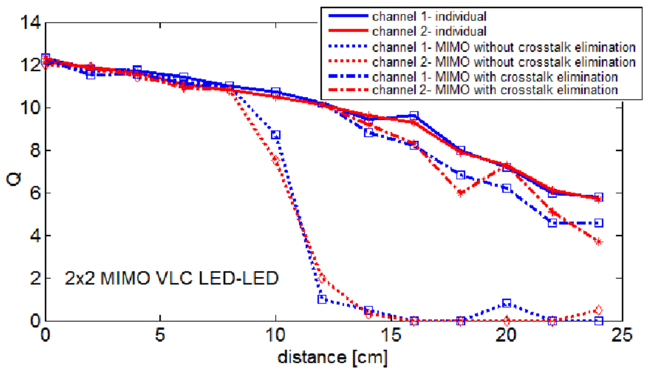

Fig. 3. The values of Q-parameter obtained for different realizations of 2×2 MIMO LED-LED VLC.

and receivers is less then 8 cm, is comparable and also the same as in the cases when transmissions were realized separately for each channel (no crosstalk). This reflects the fact that below the threshold the inter-channel crosstalk is negligible. Above this threshold the quality of received signals for the setup without elimination of the crosstalk sharply decreases. This shows the necessity of the crosstalk elimination using appropriate methods. With the application of such methods a significant improvement of the reception quality was obtained. Transmission quality, obtained in this way, for both channels above the threshold was only slightly worse compared to the quality which was achieved for individual channels separately. It means for us that system information capacity was increased almost two-times. Moreover, it is very probable that implementation at the receiver side of more advanced algorithms, than ZF, of the crosstalk elimination, like the maximum likelihood or the minimum mean square error, for example, could give additional improvement, approaching the information capacity of the system to its maximum possible value, which in this case means its doubling.

4. Summary and conclusion

The VLC is a very promising technology, deployment of which should give a lot of benefits. However, some crucial issues must be solved first. Among them are the assurance of the effective feedback channel as well as a possibility of data transmission with high throughput. The first one can be addressed by application of the LEDs in a dual role. Using of one-colour LEDs in a role of photodetectors in many cases is possible, if they will be polarized accordingly. While the second one can be solved by using of the MIMO technique, i.e. the approach which is well-known from radio transmission domain. The presented experimental results, prove that the postulated concept of using LEDs in a double role, combined with the MIMO technique, has a chance to be applicable in practice. Successful two-channel transmissions MIMO-VLC LED-LED were realized by using only ono-colour LEDs, which were used both as the light emitters and light detectors. To the best of author's knowledge this is the first time, when such approach is proposed. Obviously, the distance of approximately 20 cm for which the high quality of transmission were obtained for both channels, without a necessity of application of any additional correction methods, like forward error correction, does not look very impressive at first glance. However, we must remember that in the presented experiment single LED diodes were used in the role of transmitters. There is a more realistic scenario in which numerous group of LEDs will be used as one transmitter instead of a single LED, both at the side of transmitter as well as receiver. It means that the transmitted optical power will be much higher and also the effectiveness of photodetection process will be increased as a consequence of increasing the active surface of detection. Moreover, an increase of the distance between transmitter and receiver can be obtained also by using of additional optical equipment like lenses or specialized light concentrators.

The proposed approach, based on using of LEDs in a double role in combination with the MIMO technique, in VLC transmission systems, due to a typical construction of LED light lamps, can be a cost-effective solution. However, a continuation of more advanced research in this area is necessary.

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