Visible Light Communication: a Brief Review

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Abstract

A brief review is devoted to an evolving technology of visible light communication. The information volume transferred between users is increasing and visible light communication is becoming the option for organizing information transfer channel due to the license free broadcasting frequency range, high communication channel capacity, high noise-immunity, and high-level communication channel security. The paper presents various data transfer systems based on white phosphor LEDs and RGB LEDs by various modulation and signal processing schemes to increase the data rate.

Keywords: Visible light communication (VLC); Optical wireless communication (OWC); Free space optics (FSO); OFDM, QAM modulation; Li-Fi

1. INTRODUCTION

The increasing of data rate transfer is a novel challenge for researchers and engineers. The data volume grows up extensively every year and data transfers technologies have to answer this challenge. Radio frequency (RF) range already involved in various communication systems, but it has restrictions on the carrier frequency and broadcast band. Furthermore, the Internet of Things (IoT) is intensively growing field of industry and it requires the high quality, secure, and wide-range bandwidth communication between devices The visible light communication is one of technologies solving the RF range problems.

Visible light communication (VLC) is a novel technology of data transfer using the visible light for data transfer by LEDs and laser diodes. The usage of optical-frequency carrier allows organize secure data transmission channel which does not require any licenses for broadcast bandwidth. VLC systems potentially have 10000 times more channel capacity than RF wireless communication systems due to working at frequency range of 400–800 THz.

One of VLC technologies is the Li-Fi (Light Fidelity) [1–3]. Li-Fi is a duplex wireless data transfer system implementing intensity modulated LED-based lightning. The LEDs radiation intensity modulation at high frequencies is not noticeable to the human eye, however, it is successfully detected by modern semiconductor photodetectors, which allow to combine two functions into one Li-Fi system — artificial lightning and broadband Internet access [4,5].

White phosphor LEDs are widely implemented as artificial lighting sources now. But the maximum data transfer rate with phosphor LEDs is limited because phosphor has a long upper-state lifetime about 5–20 ns. Thus, the phosphor significantly restricts the LEDs bandwidth, typically at frequencies about 50–200 MHz [6].

The alternative sources of the white light are the RGB (red, green, blue) LEDs which consist of three chips radiating three visible wavelengths — red, green, and blue. This LEDs are not limited by the upper-state lifetime of the phosphor and have wider bandwidth up to 300–500 MHz [7]. Besides, the VLC systems based on the RGB LEDs are able to utilize the wavelength division multiplexing leading to the growth of the transfer data rate [8].

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2. WIRELESS COMMUNICATION BASED ON PHOSPHOR LEDS

In visible communication systems, the IM–DD (intensity modulation–direct detection) method is frequently used, which allows to simplify transmission and receiving of optical signal but has a lower noise immunity compared to other methods of coherent detection (Fig. 1).

The first VLC systems used the OOK (on-off keying) modulation scheme due to its ease of implementation [9–11]. However, such a modulation scheme has a wide broadcast band, and provides low data rates (10–100 Mbit/s) [9].

VLC system proposed in Ref. [12] uses a blue laser diode (LD) with a cerium(III)-doped yttrium aluminum garnet (YAG:Ce) phosphor as transmitter. It is shown the application of YAG:Ce phosphor and blue LD provides significant increase in the bandwidth of the radiation source because a LED has bandwidth about 100 MHz, but a LD has bandwidth about 1 GHz. Thus, the authors obtained wireless optical communication channel with data rate of about 2 Gbit/s.

The data rate of VLC systems with OOK modulation is limited by the narrow bandwidth of LEDs, therefore, multiplexing of the communication channel was suggested to increase data rate. Orthogonal frequency division multiplexing (OFDM) [13–15] was proposed as one of the options for multiplexing in Li-Fi systems, with first application for VLC systems in 2001 [16].

The OFDM technology makes it possible to increase the efficiency of using the radio frequency spectrum, simplify the hardware of the receiving and transmitting modules, reduces the impact of inter-symbol interference (ISI) and inter-subcarrier interference (ICI), which ensures the possibility of multipath signal propagation, and allows the use of various modulation schemes for each subcarrier to provide the best compromise between system noise immunity and data rate.

However, the OFDM technology needs to be adapted for effective work in the VLC systems. For example, in Ref. [17] the authors proposed to implement novel original technologies: asymmetrically clipped optical OFDM (ACO-OFDM) on odd subcarriers and DC biased optical OFDM (DCO-OFDM) on even subcarriers, which allows obtaining the values of the bit error ratio (BER) about 10^{-4} and one bit energy to the noise power density ratio in additive white Gaussian noise (AWGN) from 10 dB to 25 dB.

In Ref. [18] D.W. Dawoud et al. proposed another novel method of unipolar OFDM technology (U-OFDM) for data transfer in VLC systems. The authors presented simulation results for IM–DD channels of VLC systems and showed that the designed modulation method would allow increasing the signal to noise ratio (SNR) by at least 3 dB relative to the well-known ACO-OFDM technology, and up to 10 dB compared to DCO-OFDM modulation scheme.

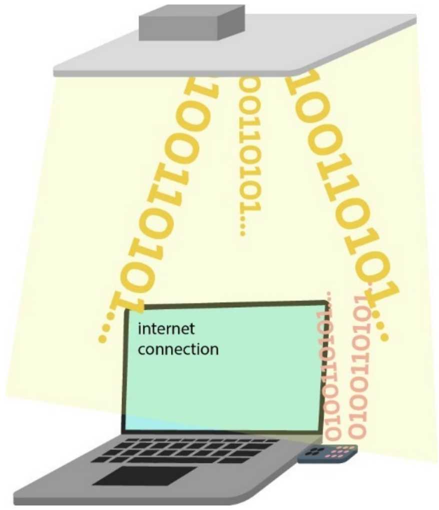

Fig. 1. Wireless optical communication system in the visible wavelength range.

The power supply of LED lighting sources is most often realized by means of pulse-width modulation (PWM) at frequencies of several kHz which also makes it possible to dim the lighting by changing the PWM duty cycle. H. Elgala and T.D.C. Little in their work [19] presented the results of modeling reverse polarity optical OFDM (RPO-OFDM) technology for gigabit VLC networks. The technology proposed by the authors performs optical OFDM (O-OFDM) modulation of the PWM signal that feeds the LED lighting device in such a way, that during the high-level state of the PWM signal, reverse polarity O-OFDM modulation is performed, and during the low-level state of the PWM signal, direct O-OFDM modulation is used. The authors showed that the use of RPO-OFDM makes it possible to transmit data through a dimmable lighting device with BER values from 10^{-6}.

Modulation schemes in VLC systems are not limited to OFDM technology. For example, in Ref. [20] carrier-less amplitude-phase modulation (CAP) is used to modulate a commercially available phosphor white LED. As a result, the authors were able to demonstrate a data rate of 1.1 Gbit/s with a maximum BER of 10^{-3} at a distance of 23 cm between transmitter and receiver. BER measurements for 128-CAP, 64-CAP, 32-CAP modulations at 110 MBaud, 170 MBaud, and 220 MBaud symbol rates with and without pre-compensation were presented.

The limiting modulation frequency of phosphor LEDs is defined by the frequency response of the phosphor. Consequently, it is not possible to obtain data rates of more than 1–2 Gbit/s. VLC systems based on RGB LEDs enable channel multiplexing not only by OFDM methods, but also by wavelength division multiplexing (WMD) methods, where each color of an RGB LED transmits a separate parallel information flow, which allows to significantly increase the data rate.

3. WIRELESS COMMUNICATION BASED ON RGB LEDS

RGB LEDs permit to significantly increase the data rate in VLC systems due to the absence of a phosphor in them that limits the bandwidth of the LED, as well as the possibility of using WDM for parallel transmission of information to channels at different wavelengths of visible radiation (Fig. 2).

In Ref. [8] authors presented a VLC system based on RGB LEDs with a downlink organized using red and green colors of radiation, and an uplink using a phosphor LED. Most often, LEDs have a rather steep slope in the amplitude-frequency characteristic, so the authors used pre- and post-equalization to obtain a flat frequency response. Quadrature amplitude modulation orthogonal frequency-division multiplexing (QAM-OFDM) technology of modulation with 64 subcarriers was used, which made it possible to provide a bit rate with maximum value of 575 Mbit/s with a BER of about 10^{-3}. However, data transmission was carried out at distances up to 80 cm, which does not allow using the proposed system for combining illumination and data transfer.

Due to narrow bandwidth of LEDs, it becomes necessary to efficiently use the available bandwidth to modulate the radiation. To do this, discrete multitone modulation, which occupies the entire available frequency spectrum is used. Thus, in works [21–23] authors reached the data rates up to 3.4 Gbit/s, using various equalization algorithms on the receiving side. However, in these works, record data rates were achieved by the calculation method. In laboratory conditions, at relatively short distances between the receiver and transmitter (up to 1 m), the bit rate was measured for each channel of the WDM system, after which, using mathematical calculations, rates from 1.25 to 3.4 Gbit/s were obtained.

Data rates over 4 Gbit/s per channel have been obtained by other methods of signal modulation. The paper [24] presents a data transfer rate of up to 4.4 Gbit/s for each WDM channel, but laser diodes of three RGB wavelengths were used as a transmitter, since laser diodes have a much higher speed than LEDs. The BER was about $3{\cdot}10^{-3}$ with an SNR of 15.3 and an error vector amplitude of about 17%. However, the distance between the transmitter and receiver remained low, about 20 cm, which limits the application possibilities of this scheme.

Data transmission for a longer distance in the VLC system was presented by Y. Wang et al. [25]. The authors demonstrated a VLC system based on RGB LEDs, which allowed obtaining data rates up to 4.5 Gbit/s and a BER

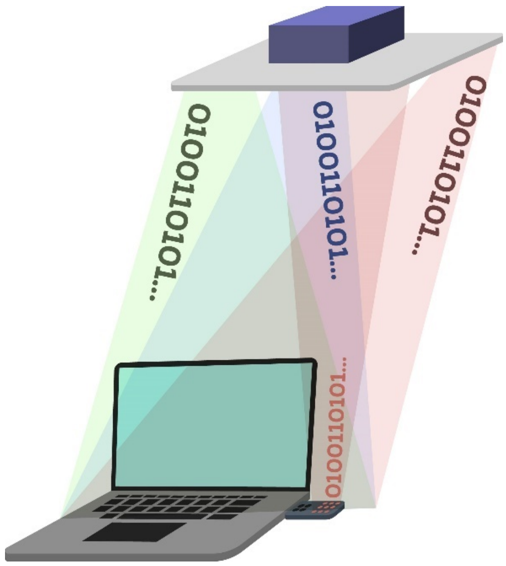

Fig. 2. Visible light communication system based on RGB LEDs.

of the order of $3.8{\cdot}10^{-3}$ at a distance of more than 1.5 m. This data rate was obtained by CAP modulation scheme combined with recursive least square based adaptive equalization.

4. VLC SYSTEMS COMPATIBLE WITH IEEE 802.11 PROTOCOL

The inception of VLC systems into the existing infrastructure is costly due to the different set of architectures and data transfer protocols. Therefore, in the early stages of the growth of the VLC market, solutions as compatible as possible with current data transmission systems are needed. At the moment, the most common family of standards governing wireless networks is the IEEE 802.11. In Refs. [26–28], a duplex VLC system based on white phosphor LEDs and compatible with existing Ethernet networks was presented. The transmitter was based on a Wi-Fi modem with output signal adapted to modulate LEDs, that made it possible to connect the system to the Internet without additional interfaces. According to calculations, the expected data transfer rate should have been up to 100 Mbit/s at a distance of up to 4 meters between the transmitter and receiver, however, due to the effect of additive white Gaussian noise on the communication channel, the speed was 40 Mbit/s at this distance.

A similar system, but based on RGB LEDs, was presented in Refs. [29–31]. An Internet connection speed of 65 Mbit/s at a distance of 2 m between the transmitter and receiver, and 42 Mbit/s at a distance of 4 m was demonstrated. Moreover, the use of RGB LEDs as a source of radiation allows to control the color of lighting within the Human Centric Lighting concept. This concept proposes to introduce adaptive artificial lighting, which will change color in accordance with the change in color during daylight hours of a natural lighting — the Sun. Such an adaptive change in lighting can favorably affect the productivity and overall well-being of consumers [32,33].

5. CONCLUSION

Developing visible light transmission technology can solve several existing problems inherent in radio frequency wireless networks. VLC systems do not require licensing of the broadcasting frequency range, data transmission has a high security level due to the fact that it is limited to direct visibility between the transmitter and receiver and allows to combine the functions of lighting and data transmission in one device, which will improve energy efficiency and ergonomics of household devices.

Li-Fi technologies has high noise immunity, intersymbol interference and interference between subcarriers, and the review shows that data transmission over visible light can provide users with high-speed Internet access at data rates of the order of several Gbit/s, and the increasing use of RGB LEDs for development of such systems will improve the quality of lighting within the concept of Human Centric Lighting.

The application of VLC technology is becoming relevant due to the intensive development of the IoT, which requires the presence of broadband communication channels that will not interfere with each other. Taking into consideration the small information volumes from IoT devices, Li-Fi is becoming the most appropriate way to transfer information between IoT devices.

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Связь в видимом диапазоне длин волн: краткий обзор

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Аннотация. Короткий обзор посвящен такой развивающейся технологии, как связь по видимому диапазону длин волн. С ростом количества передаваемой информации между пользователями связь по видимому свету становится все более актуальной опцией организации каналов передачи информации благодаря отсутствию необходимости лицензировать частотный диапазон вещания, высокой емкостью канала связи, высокой помехоустойчивости, высокой защищенности канала связи. В работе представлены различные системы передачи данных на основе белых люминофорных светодиодов и RGB светодиодов, которые используют различные схемы модуляции и обработки сигнала для повышения скорости передачи информации.

Ключевые слова: связь в видимом диапазоне длин волн (VLC); оптическая беспроводная связь (OWC); free space optics (FSO); OFDM, QAM модуляция; Li-Fi