Improving Efficiency of a Wireless Optical Data Transmission Channel in the Visible Wavelengh Range

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***Abstract*—The article is devoted to the study of a wireless optical communication channel in the visible wavelength range. In the first part of the study, an original method for encoding binary data stream based on QPSK quadrature phase shift keying and color separation in a wireless optical communication channel in the visible range has been proposed. A unique feature of the proposed method is the independence of the light intensity and color hue of the bit sequence values. The proposed method has improved speed and an error detection mechanism in the channel. In addition, the developed coding method is suggested as a source of information for adaptive power control of the luminous flux on the basis of monitoring the state of each of the color components, and the synchronization problems of the receiver and the transmitter are considered. These features allow us to implement the proposed method of coding and dynamic control of the intensity for the luminous flux in artificial light sources based on RGB LEDs for the organization of wireless data transmission channels, to use these light sources in rooms with combined lighting. The paper also contains the estimate result of the maximum distance at which recognition of an optical signal is possible based on the quantum threshold of detection. Estimation of errors in an optical channel, as well as the level of general illumination by lamp or sunshine light sources in the room will dynamically change the optical signal level (or sensitivity of the photodetector) and ensure the required security of information during its transmission in controlled space based on the quantum threshold value detection.**

Keywords—wireless data transmission, optical data transmission channel in the visible wavelength range, quantum threshold of optical emission detection, color channel, encoding based on quadrature phase shift keying.

I. Introduction

One of the relevant development directions for modern communication networks is the implementation of wireless data transmission channels. The utilization of the radiofrequency spectrum comes with significant limitations due to the regulations on radiofrequency usage and utilization of transmitting/receiving devices in the radio wave range. As an alternative to the traditional wireless channels, the works of recent years suggest to utilize modulated light flow from light sources in the visible wavelengh range [1-8]. A modern technology of wireless optical data transmission – VLC (Visible Light Communication), which uses light emitting diodes (LEDs) as transmitters, is not only comparable (by its transmission speed) to existing wireless data transmission technologies in the radio wave range, but also has significant potential for the future development.

The approach suggested to organize a wireless optical data communication channel consists of applying three-component (RGB) LEDs to illuminate a room (or its separate areas) and transmit information.

II. Encoding Based On Quadrature Phase Shift Keying

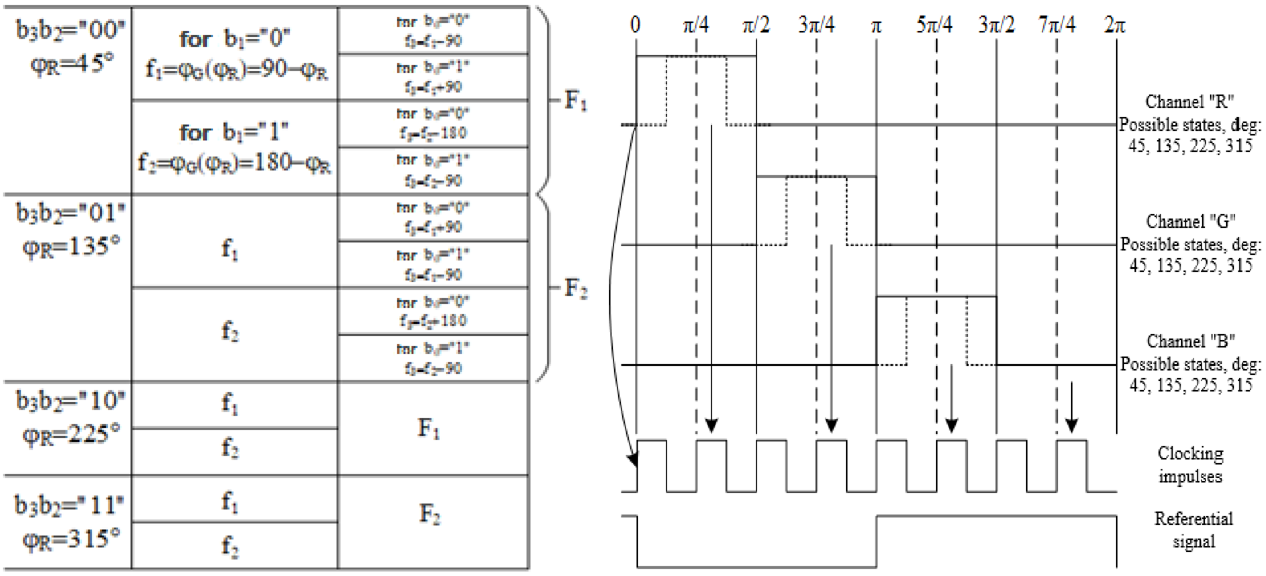
It is known [9] that the human eye is unable to detect light flow pulsations at frequencies higher than 100 Hz. Thus, applying pulse modulation in the frequency range of 100 kHz – 10 MHz allows to provide data transmission and room illumination without adverse health effects. Additionally, transmission of information via a wireless optical channel allows to determine the protected zone perimeter quite precisely in order to ensure confidentiality of the transmitted data. Utilization of the optical range decreases the probability of attacks targeted at hindering information accessibility.

The suggested encoding method is demonstrated in figure 1a. Sequential flow of incoming data bits $I(t)$ is transformed into a sequence of N – bit blocks $(b_N, b_{N-1}, \ldots, b_1, b_0)$, where each block is encoded with one packet of RGB impulses. In this case, the term «packet of impulses» implies the conjunction of impulses by each of the color channels during the period of referential signaling. Data encoding by each of the color channels is achieved based on quadrature phase manipulations with four possible phase states relative to the referential signal (45°, 135°, 225°, 315°). Therefore, the number of color channels is $CC = 3$, the amount of possible phase states is $FC = 4$, the total quantity of unique combinations according to the rules of combinatorics is $M = CC^{FC} = 3^4 = 81$.

As an additional restriction, let us define that per one referential signal period, each color channel forms no more than one impulse, as well as that one period cannot include two and more impulses with equivalent phase. Thus, let us define the number of unique phase states as

$$M = \prod_{j=0}^{CC-1} (FC - j) = 4 \cdot 3 \cdot 2 = 24 \qquad (1)$$

When encoding binary signals, the number of bits transmitted during a period of one referential signal is determined by equation



a) b)

Fig.1. The table of phase states and the diagram of information encoding based on phase manipulations in a channel with spectral division

$$M_2 = div\left[\log_2 \prod_{j=0}^{CC-1} (FC - j)\right] = 4 \qquad (2)$$

According to (2), in the case of binary data flow input $I(t)$, the number of bits in each transmitted block is 4.

The remaining 8 states can be used to transmit service messages, such as the begin/end transmission signal, error presence indication and data flow control. This encoding approach presupposes that during the referential signal period, each color channel forms one impulse of equal length, and all three of the color components will have different phases. Not only this allows us to provide the constancy of color and light flow intensity during transmission of random data flow, but it also increases the noise immunity by the means of simultaneous control of all the color components on the receiving end. The simultaneous presence of two or three impulses with different colors on the input will be an indicator of noise or «light flooding» - a change in the intensity of additional natural or artificial lighting. Here it is necessary to distinguish short-term impulses ($\tau \approx 10^{-8} \div 10^{-6}$ s) within three color channels, which are determined as an error in the active phase of data transmission or used to synchronize the clock generators of the receiver and the transmitter between data packets, from slow-shifting signal ($\tau \approx 10^{-3} \div 10^{1}$ s) on the input of the receiver, which is typical for «light flooding» with natural or artificial light. During the formation of the synchronizing impulses, it is suggested to have simultaneous impulses in all color channels for phase state $\varphi = 45°$. Figure 2 represents the flowchart for the signal analysis algorithm in the receiving tract.

Such methodology provides control and the ability to dynamically compensate for external «light flooding» by the means of changing the photoreceiver amplification coefficient and regulating the brightness of the LEDs.

The encoding diagram for one of the possible states for each channel is described on figure 1b. The dotted line on the figure represents the ability to implement pulse-width modulation (PWM) for intensity of the light flow, which allows to provide brightness adjustability for the illumination equipment and achieve comfortable working environment or to carry out adaptive adjustments of light flow intensity based on the light source with respect to luminance changes in the room. An analogous technology is suggested in [10].

It is worthwhile to point out that the process of adjusting the illumination power when LED-based light sources are used as the transmitters has its own limitations bound to creating the required luminance or compensating for external «light flooding». Automatic adjustments of photosensitivity for the photoreceivers have a priority before power adjustments for the light sources, since it allows to independently fine-tune the total amount of luminance and to compensate for the constant component from additional light sources.

III. Quantum Detection Threshold

In the case when stationary light flow enters the photodiode, it begins to generate pairs of charge carriers as independent arbitrary events. As is known [12, 13], this photon transformation process obeys the Poisson statistics, i.e. when optical energy E_R enters the photodiode during a particular time interval, it should be expected that N pairs of charge carriers will be created, where

$$N = \eta \frac{E_R}{E_{ph}} = \eta \frac{E_R \lambda}{hc} \quad (3)$$

η - photodiode quantum efficiency, E_{ph} - photon energy.

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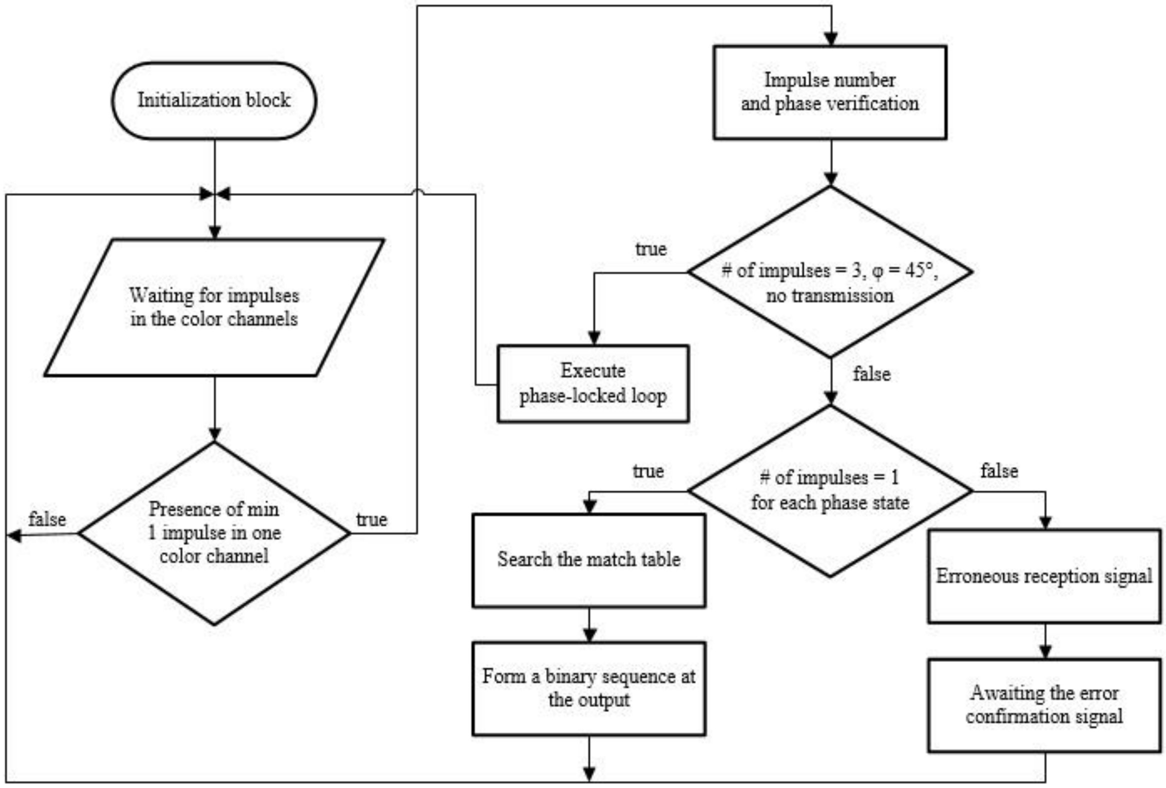

Fig. 2. The algorithm of signal analysis in the receiving tract

The probability that the number of created charge carrier pairs equals to k is determined by the Poisson probability distribution:

$$P(k \mid N) = \frac{N^k}{k!} \cdot e^{(-N)} \quad (4)$$

In this case, the standard deviation from average value N will be equal to N as well. In an ideal communication system, a change in the number of generated charge carrier pairs is the only source of noise [14]. Aside from that, optical energy enters the input of the photodiode and the charge carriers are generated in the input link only when logical «1» is transmitted within the according color channel. Let us assume the level of sensitivity for the receiver to be of such a value that would make it possible to detect one P-N junction.

Therefore, there is no possibility for errors when logical «0» is received, but the possibility arises in the case when optical energy that enters the functional surface of the photodiode does not lead to the generation of electric charge carriers. With an equiprobable appearance of logical «0» and «1» in the digital stream, using the Poisson distribution, we get:

$$PE = \frac{1}{2}\left[\frac{N^{0!} \cdot e^{(-N)}}{0!} + 0\right] = \frac{1}{2} e^{(-N)} \quad (5)$$

Thus, for $PE < 10^{-6}$, it is necessary to absorb $N > 13$ photons, i.e.

$$E_R = \frac{N \cdot E_{ph}}{\eta} > \frac{13 \cdot E_{ph}}{\eta} \quad (6)$$

In this case, the minimal average power on the input of the photoreceiver

$$\bar{\Phi}_R = \frac{1}{2} E_R \cdot B > \frac{10 \cdot E_{ph} \cdot B}{\eta} \quad (7)$$

When $\eta = 1$, equation (7) describes the absolute quantum threshold of detectability for each of the color channels. With $\lambda = 0,65$ mcm, $E_{ph} = 1,91$ eV and $\bar{\Phi}_R > 3,056\ \frac{\text{pW}}{\text{Mbit/s}}$.

As the research has shown [14], heat noise of modern amplifiers is almost two orders of magnitude higher than the quantum threshold.

Hence, when $\eta = 1$ and the appearance probability for «0» and «1» in the digital stream is equal, according to the quantum detection threshold, a single bit accounts for seven photons.

Under the condition when light is distributed inside a single half-space (hemisphere), the optical emission power that projects to the functional surface of the photodiode can be evaluated as

$$P = \frac{P_{em} \cdot K_{dp}^{em}(\theta) \cdot K_{atn} \cdot S_{sp}}{2\pi R^2} \quad (8)$$

where P_{em} - power emitted by the light source, W; $K_{dp}^{em}(\theta)$ - attenuation coefficient, explained by the directivity pattern of the receiver and the transmitter; K_{atn} – attenuation coefficient, due to dispersion of the optical signal in the atmosphere; S_{sp} – spatial size of the sensitive zone of the photoreceiver; R – distance between the transmitter and the receiver.

Attenuation of optical signals propagated in optically translucent mediums obeys the law of Bouguer-Lambert-Beer and has the following form:

$$K_{atn} = e^{-(K_{atm} \cdot R)} \quad (9)$$

where K_{atm} – index of absorption in the medium, for the atmosphere $k_{atm} = 75\ dB$, while $K_{atm} = \frac{4\pi k_{atm}}{\lambda}$.

For the atmospheric transmission systems based on optical emission in the visible wavelength, the power (equation (8)), according to [15, 16] can be rewritten as

$$P_{sp} = H_0 \cdot P_{em} \quad (10)$$

where $H_0 = \frac{(m+1) \cdot \cos^m(\varphi) \cdot S_{\text{пр}}}{2\pi R} \cos\Psi \operatorname{rect}\Psi$; φ – angle between the normal of the receiver and the vector of the light flow entering the receiver, rad; $\operatorname{rect}\Psi = \begin{cases} 1, \text{if } \ \Psi \le \Psi_{vr} \\ 0, \text{if } \ \Psi > \Psi_{vr} \end{cases}$, where m – coefficient of light energy density concentration, $m = \frac{\lg(\cos(60°))}{\lg(\cos(\Phi_{vr}))}$; Φ_{vr} – visibility range of the transmitter according to the half-power borderlines of the directivity diagram, rad; Ψ_{vr} – visibility range of the receiver according to the half-power borderlines of the directivity diagram, rad.

Figure 3 demonstrates the geometric location of the receiver and the transmitter.

From equation (10), let us derive the distance between the receiver and the transmitter

$$R = \sqrt{\frac{(m+1) \cdot \cos^m(\varphi) S_{sp}}{2\pi P_{sp}} \cos\Psi \operatorname{rect}\Psi} \quad (11)$$

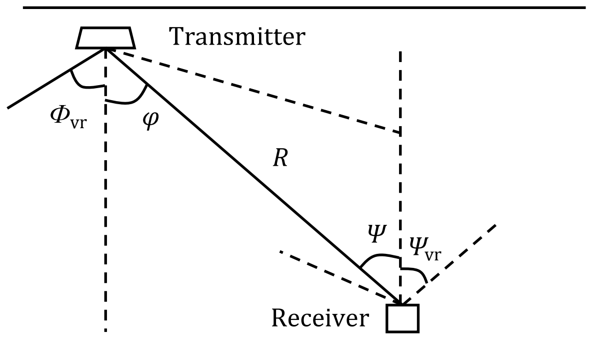

Fig. 3. The geometry of the optical data transmission channel

For the receiver based on the BPW 34B photodiode and the transmitter based on the SMD RGB 5050 light emitting diode module (9 pcs.), the evaluation of the distance at which it is possible to obtain unauthorized access to the transmitted information has shown that under conditions of optical translucent medium without any obstructions, a physically realistic threshold of signal detection is a distance of 30-35 m. The initial data for the evaluation was represented by the following values: $S_{sp} = 7$ mm, $P_{sp} = 3{,}056$ pW, $\Psi_{vr} = 60°$, $\Phi_{vr} = 60°$, $P_{msr} = 0{,}17$ W.

Figure 4 represents the functional scheme of the device used to implement the suggested encoding method in a wireless channel based on optical emission. The incoming data flow of binary sequence $I(t)$ is fed to the input of the digital data processing device (DDPD). The functionality of the DDPD block is: to form a sequence of rectangular impulses for synchronization with a data source, to buffer incoming data and control the flow, as well as to transform a bit sequence into a sequence of four-bit blocks. The synchronization signal enters the input of the clock generator to apply the phase-locked loop (PLL) mechanism, outgoing data flow enters the input of the sequential encoding device (SED). The SED functional algorithm is shown on figure 1a. Outgoing signals from the SED block enter the PWM-based illumination intensity regulating blocks, then proceed to the LED controlling current switches (CS).

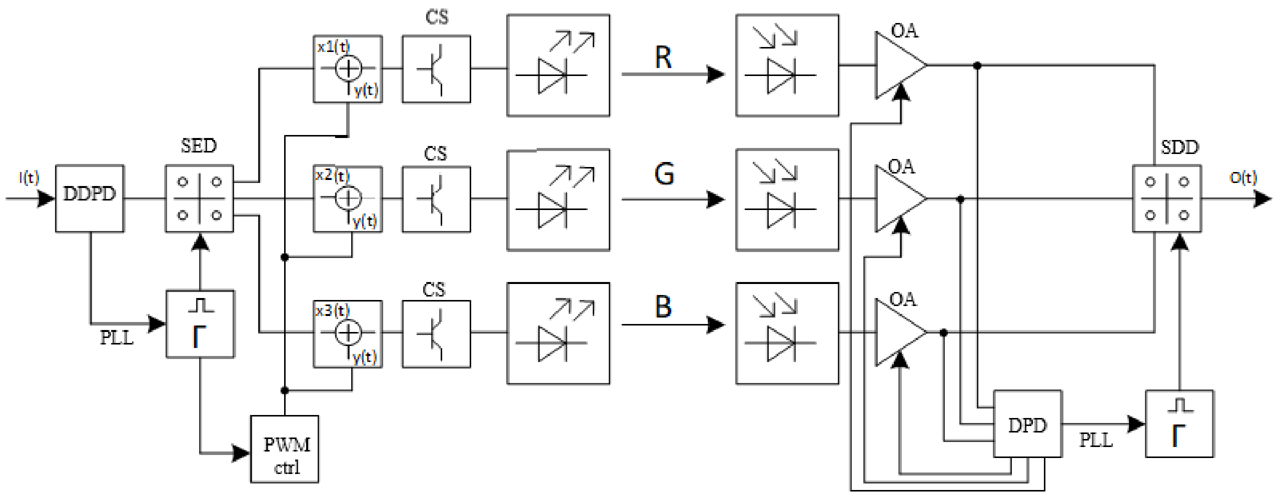

Fig. 4. The functional scheme of the device required to implement the suggested encoding method

The receiving side consists of the photoreceivers (photodiodes) with the corresponding optical color filters, which transmit the signals to the inputs of the operational amplifiers (OA) with an adjustable amplification coefficient. Afterwards, the signal enters the input of the data processing device (DPD). The primary functions of the DPD are to form a rectangular impulse sequence for synchronization between the transmitter and the receiver, and also to analyze the signal state for each of the color components (to determine the presence of errors or «light flooding»). In parallel, the signals from the outputs of OAs for each color channel are transmitted to the sequential decoding device (SDD), which carries out an algorithm that is inverse to the original one. The output data flow of the binary sequence is formed at the output of the SDD.

IV. CONCLUSION

The advantages of the suggested approach are multiple. They include: increased data transmission speed in wireless channels based on the VLC technology; improved noise immunity due to the applied encoding technology and the compensation algorithm used to account for fluctuations in light flow of an external light source («light flooding»); significant protection of the channel from unauthorized data access achieved via distributed spectral encoding and the ability to more efficiently filter light flow from the VLC-transmitter in the red and blue color spectra.

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