Wireless local data transmission network through LED lighting compatible with IEEE 802.11 protocol communication systems

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Abstract. We developed a wireless duplex communication system using visible light communication concept. In this work we investigated a downlink data transmission channel. We modelled the optical configuration of the system, calculated optical losses, fabricated the system and measured downlink channel parameters under test of analog and digital signals. The analysis showed that with a heterodyne scheme used for transmitting signals through visible light, the model of additive Gaussian noise is applicable to the channel and there are no phase distortions in the system. The system has shown the capability to operate with modulation types according 802.11 IEEE protocol.

1. Introduction

The global issue of modern wireless communication systems is limitation, and as a result, shortage of radiofrequency (RF) range, therefore new wireless data transmission technologies are emerging. One of these technologies, named «Li-Fi» [1,2], can be used as an additional one, or sometimes as an alternative to wireless radio-frequency systems, such as Wi-Fi and Bluetooth. This technology proposes to use visible light emitting diodes (LEDs) in lighting systems as a carrier for information signal [3,4]. Although the capacity of visible spectrum for data transmission is higher compare to microwaves, there are some technical limitations for usage of this capacity. White phosphorus LEDs, which are usually used as sources of visible radiation, have rather large raise- and fall-time due to phosphor inertia. Moreover, dimensional parameters of commercially available chips used for lighting and providing necessary power for illumination resulting in high parasitic capacitance of LEDs and limits the switching speed. Similar technical parameters restrict the speed on the receiver side: high sensitive, large active area photodiode (PD) chips have large capacitance and are not able to switch as fast as it is necessary to use the whole capacity of visible spectra range. In this work, we proposed a scheme for transmitting data through LEDs and implemented the downlink part on commercially available components, investigated losses and noise in the proposed system, and also demonstrated possibility of transmitting digital signals with modulation schemes commonly used in wireless radio frequency networks.
2. Data transmission system description
The system block-diagram is shown on figure 1. We developed the transmission system using heterodyning. On the one hand, this approach allows automatically switch between different types of modulations using Wi-Fi modem, on the other hand, it makes the system fully compatible with 802.11 IEEE protocol and access to the global network directly from the local network. The system includes a master module and a slave module. The master module is implemented in a shape of office lamp and has an Ethernet interface for connection to global network. The key components of the master module are: modem setting the modulating signal according to protocol IEEE 802.11, frequency shifting circuit, impedance matching circuits, LED array of 16 white phosphorus LED for the downlink channel, and photodetector array of 4 photodetectors of near-infrared spectral range for detecting the signal in the reverse channel. The slave module also has the Ethernet interface for connection to the internet. The slave module consists of: 2 photodetectors converting the received light signal into an electrical one, IR laser to build an uplink channel, and the modem. The master and the slave modules are placed in front of each other on distance D.

![Figure 1. Block diagram of developed data transmission system.](image-url)
3. Optical model and calculations

A model of the system’s downlink optical part was firstly created to build analog VLC link (see figure 1) and estimate optical loss in the system with various types and number of LEDs and PDs. The model was set up in Zemax software package. The model of luminous source is based on its dimensional and case parameters. A single source specified with the luminous area and lens system. LED array is represented as a set of single sources with a given angular distribution of luminous intensity. The receiver model takes in to account photosensitive area of single element, its case, lens system, number and mutual arrangement of PD. Case parts limit the passage of radiation to the photosensitive area, forming the angular characteristic of the PD. After specifying a system consisting of a source and receiver, the path of the rays is calculated, which makes it possible to estimate the fraction of energy that has reached the receiver in particular source and receiver configuration and estimate the loss of radiated energy taking into account the geometric constraints associated with the size of the receiver and remoteness from the radiation source.

The next step was to calculate photodetector current according relation (1), using coefficient $\eta_{opt}$ which is a result of the model computation. Figure 2 illustrates calculations in terms of spectral characteristic of the source and the receiver.

$$I_p = \eta_{opt} \int \Phi_{eLED}(\lambda) \times R(\lambda) d\lambda$$  \hspace{1cm} (1)

![Figure 2](image)

Figure 2. Normalized spectral characteristics of the PLCC5630 white LED with correlated color temperature (CCT) 5500K and the FDS100 photodiode, where: $R(\lambda)$ - spectral sensitivity of the photodiode, $\Phi_{eLED}(\lambda)$ - spectral distribution of luminous flux, $\Phi_{eLED}(\lambda) \times R(\lambda)$-part of the signal delivered to the photodiode active area.

The model was verified by measuring photocurrent on a single photodiode (with a lens) illuminated by an 8 x 8 LED array with lenses at different distances. The discrepancy between the calculated and experimental data was less 8%. Decreasing of energy received by photodetector in proportion to the square of the distance from the source is fulfilled at distances of more than 1.5 m.

Then we assumed channel model as additive white Gaussian noise (AWGN) to estimate channel capacity $C$ according to Shannon–Hartley theorem, equation (2),

$$C = B \log_2 (1 + SNR), \hspace{1cm} (2)$$

where, $B$ is the channel bandwidth, $SNR$ is the signal-to-noise ratio.

The SNR can be calculated according equation (3). Noise in PD has three main sources: photon noise, dark current noise, thermal noise. Calculations shown, that thermal noise is the dominant mechanism for investigated PDs.

$$SNR = \frac{n^2 I_p^2 R_i}{8ek_B TB}, \hspace{1cm} (3)$$
where \( n \) is RF signal modulation depth (current modulation depth on PD), \( I_P \) is the PD light current calculated using formula (1), \( R_L \) is the load resistance, \( e \) is the electron charge, \( k_B \) is the Boltzmann constant, \( T \) is the system’s temperature, and \( B \) is the electrical bandwidth of PD.

Equation (3) takes into account only the thermal noise of the photodetector generated by the input optical signal, and does not take into account the noise of the further data transmission scheme. We considered \( n=1.1 \) in this calculation as we modulate LEDs by small signal near operating point. The results of the calculation are presented in table 1.

**Table 1.** Calculated SNR for system of 8x8 LED array with lenses and single photodiode with lens.

| Distance (m) | SNR  |
|-------------|------|
| 2.0         | 33.2 |
| 2.5         | 15.0 |
| 3.0         | 7.45 |
| 3.5         | 4.66 |
| 4.0         | 2.43 |

Such computations were made for several combination of sources, receivers and optical elements: LEDs of standard size - PLCC 5630 with CCT 5500K, PLCC 2835 with CCT =4000K, photodiode FDS100 with lenses LA1576 with and without antireflection coating and own-manufactured lenses. Lenses on LEDs reducing the angle of radiation 120° to 60°. We used criteria of reaching the compromise between expected channel capacity providing data transmission rate not less than 100 Mbit/s, power consumption not more than 40 W and luminous flux not less than 500 lm to define the resulting system design. The computation results shown that the system of 4x4 LED with lenses and 2x1 PD with lenses optimally satisfied this criterion. We designed and fabricated the lenses optimized for 60 degrees angle of incidence. The components of the system are listed in table 2.

**Table 2.** Components of the data transmission system.

| System’s part                      | Component | Model                      |
|------------------------------------|-----------|----------------------------|
| Master module                      | modem     | MikroTik RB911G-5HPacD     |
| Master module downlink part        | white LEDs| PLCC 5630                  |
| Master module downlink part        | lenses    | own-manufacture            |
| Slave module downlink part         | lenses    | own-manufacture            |
| Slave module downlink part         | PDs       | FDS100                     |
| Slave module                       | modem     | MikroTik RB911G-5HPacD     |
| Slave module uplink part           | IR Laser diode | FPL1055T           |
| Master module uplink part          | lenses    | own-manufacture            |
| Master module uplink part          | PDs       | FDGA05                     |

**4. Experimental setup**

An experimental setup for characterization of developed analog VLC link is shown on figure 3(a) and 3(b). The bandwidth of analog VLC link, loss within it and input and output reflection coefficients were measured using vector network analyzer Rohde& Schwarz ZVA40 according to figure 3(a). Keysight M8195 arbitrary wave form generator and UXR0204A oscilloscope in vector signal analysis mode, figure 3(b), were used to apply to the analog VLC link different digital modulation schemes and obtain constellation diagrams depicting the signal as a two-dimensional xy-plane scatter diagram in the complex plane at symbol sampling instants. The measurements were carried out on a pseudo-random sequence (PRBS) 2^7-1.
5. Results & discussion

The measured bandwidth of the analog VLC link on -3 dB level was 25 MHz. The input and output of analog VLC link were well impedance matched (better than -10 dB), but the receiver part had high noise level due to its electrical amplifying part. Change of the distance D between master and slave modules was limited to 2.5 m due to available for VNA coaxial cable lengths and system showed 65 dB loss on distance 2.5 m that is in a good agreement with the 67 dB losses calculated by the model described in Section 3.

Measurements according to schematic depicted on figure 3(b) showed that carrier frequencies above the measured bandwidth are suitable for digital data transmission. Figure 4 depicts signal constellations for 8PSK, 16QAM and QPSK modulation schemes with carrier frequency 40 MHz and symbol rates 10-15 Mbaud/s. The noise level increases with the increase of symbol rate, therefore, the signal band and the shape of constellation diagram (random ball about each constellation point) confirms the application of AWGN channel noise model. The constellation diagram shape revealed that the system does not exhibit phase noise that allows to use other complex and effective modulation schemes, for example FTN signals [5].

Figure 3. Experimental setup

Figure 4. Signal constellations: (a) 16QAM, symbol rate 10 Mbaud (top picture) and 15 Mbaud (bottom picture); (b) 8PSK, symbol rate 10 Mbaud (top picture) and 15 Mbaud (bottom picture); (c) QPSK, symbol rate 10 Mbaud (top picture) and 15 Mbaud (bottom picture).
6. Conclusion
The data transmission network through LEDs of visible spectrum on commercially available components has been demonstrated. Experiments showed the applicability of AWGN model for data transmission channel through LEDs. Calculations of noise in photodetector showed the possibility to transmit data on distances up to 4 m with rate up to 100 Mbit/s using the schematic proposed. However noises in electrical amplifying circuit should be reduced to reach the transmission rates up to 40 Mbit/s on distance 3-4 m. The application of QAM16 modulation scheme resulted in the smallest error vector magnitude, and the 8PSK modulation scheme gave the higher signal-to-noise ratio compared to other applied modulation schemes.

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