Mühendislik Bilimleri ve Tasarım Dergisi
10(3), 908 – 916, 2022
e-ISSN: 1308-6693

Journal of Engineering Sciences and Design
DOI: 10.21923/jesd.982720

Araştırma Makalesi | Research Article

DEVELOPMENT OF MULTICARRIER VISIBLE LIGHT COMMUNICATION SYSTEM USING ARM CORTEX-M3 MICROCONTROLLER

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Keywords

Visible Light Communication, ACO-OFDM, Optical Communication, ARM Cortex-M3, Signal Processing.

Abstract

With the development of technology, the constraints and the needs in the field of communication have increased. Especially, limited and licensed radio frequencies that can cause electromagnetic interference and health problems in the use of wireless communication make the visible light communication (VLC) technologies very important. In this study, an ARM based VLC system design has been realized to implement a unique product with the use of low-cost and commercial off-the-shelf electronic components. In this context, receiver and transmitter circuits are designed, printed circuit boards and appropriate enclosures have been produced, as a result, a system prototype has been created to use in interior applications with standard ceiling height. The design is also one of the few implementations in which orthogonal frequency division multiplexing (OFDM) modulation and digital signal processing applications are performed by using ARM based microcontroller. Consequently, the system communication is achieved at a data rate of 3.5 kbps from a distance 1.8 m to 3 m. Also the system communication is successfully performed from the center of the light source up to 85 cm distance on the direct side and up to an angle of 50° on the azimuth.

ARM CORTEX-M3 MİKRODENETLEYİCİ KULLANIMI İLE ÇOK TAŞIYICILI GÖRÜNÜR IŞIK HABERLEŞME SİSTEMİ GELİŞTİRİLMESİ

Anahtar Kelimeler

Görünür Işık Haberleşmesi, ACO-OFDM, Optik Haberleşme, ARM Cortex-M3, Sinyal İşleme.

Öz

Teknolojinin gelişmesiyle birlikte iletişim alanındaki kısıtlamalar ve ihtiyaçlar artmıştır. Özellikle elektromanyetik girişime ve sağlık sorunlarına sebep olabilecek, sınırlandırılmış ve lisanslanmış kablosuz iletişimin kullanımı, görünür ışık ile haberleşme teknolojilerini önemli kılmaktadır. Bu çalışmada, düşük maliyetli ve ticari kullanıma hazır elektronik bileşenlerin kullanımı ile ARM tabanlı özgün bir VLC sistem tasarımı gerçekleştirilmiştir. Bu kapsamda alıcı ve verici devreleri tasarlanmış, baskılı devre kartları ve bunlara uygun kutular üretilmiş, bunların sonucunda da standart tavan yüksekliğine sahip iç mekan uygulamalarında kullanılmak üzere bir sistem prototipi oluşturulmuştur. Tasarım aynı zamanda ARM tabanlı mikrodenetleyici kullanılarak, dikgen frekans bölmeli çoğullama modülasyonu (OFDM) ve dijital sinyal işleme uygulamalarının gerçekleştirildiği az sayıdaki uygulamadan birisidir. Sonuç olarak sistem iletişimi 1.8 m ile 3 m mesafeden 3.5 kbps veri hızında sağlanmıştır. Ayrıca sistem iletişimi, ışık kaynağının merkezinden direkt 85 cm mesafeye ve 50° açı yapacak şekilde başarı ile gerçekleştirilmiştir.

Alıntı / Cite

Arioglu, O., Gurkan, K., (2022). Development of Multicarrier Visible Light Communication System Using ARM Cortex-M3 Microcontroller, Journal of Engineering Sciences and Design, 10(3), 908-916.

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Makale Süreci / Article Process	
Başvuru Tarihi / Submission Date	07.09.2021
Revizyon Tarihi / Revision Date	23.02.2022
Kabul Tarihi / Accepted Date	20.05.2022
Yayım Tarihi / Published Date	30.09.2022

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1. Introduction

The existence of limited resources in the developing and crowded world has always directed people to search for new resources. Energy, food, clean water and communication channels are some of the most important ones. The increase in the population and the efforts of more people to communicate with each other in the world highlight many innovations and needs in communication technologies. The most distinctive constraint appears on electromagnetic spectrum (Zuhdi and Wafi, 2015).

The Visible Light Communication (VLC) is a communication technology using frequencies between 400 THz and 800 THz whose bandwidth is larger than radio frequencies and provides faster communication for more consumer. It is obviously seen that the bandwidth of radio frequencies used for wireless communication is not enough because of increasing the use of mobile phone and internet. The most important advantage of visible light communication is unlicensed (free), wider and clear bandwidth. Haas (2017) expresses that the need of wireless communication will reach 6 THz bandwidth in 20 years, the radio frequencies bandwidth has only 0.3 THz bandwidth and that 6 THz bandwidth is just 0.8% of visible light spectrum with infrared (IR). Also Haas takes attention that the use of Light Fidelity (Li-Fi) for next generation wireless communication 5G. Visible light communication promotes to the encouraging alternatives to wireless and cable-based communication required for 5G and Internet of Things (Kolade et al., 2020). In visible light communication systems data is sent as the transmitter light source (LED) illuminates whole region. As a result, the light is used for more than one function simultaneously by providing energy saving. The system may be one of the greenest and eco-friendly technology in consideration of high energy efficiency (Sharma et al., 2018).

VLC systems use visible light source as data carrier. It means that all light emitting devices can be used as a transmitter with the appropriate hardware addition. Televisions, LED panels, street lamps, lamps for indoor lighting, car headlights and etc. light sources can be used as data transmitter for visible light communication which means that humans can be always online when watching television, driving a car or walking on the street. Furthermore, Khan (2017) emphasizes that the radio frequency waves cannot travel good enough in sea water result of its good conductivity. This means that VLC communication can be used in underwater communication networks instead of radio frequencies.

2. Aim

Firstly, it is aimed to have a commercial device prototype that includes unique transmitter and unique receiver circuit designs, with having appropriate enclosures. These circuits must be designed by using low cost and commercial off-the-shelf electronic components. In addition, it is aimed to have low power consumption by using ARM Cortex M3 based microcontroller and to implement signal processing algorithms like ACO-OFDM modulation running on microcontroller successfully. Also it is defined as success criteria to have an error-free communication between transmitter on ceiling and receiver on table or floor for indoor applications with standard ceiling height.

3. Content

In the last century, great developments have been made in the field of wireless communication due to the limited capacity and high cost of wired communication systems. From this point on, many researches are being done to take advantage of wireless communication and many new methods are emerging. These methods are particularly concerned with the licensed radio frequencies and insufficient bandwidth capacity. The visible light communication has an important role in these researches due to its advantages and bandwidth capacity. Frequency distribution on electromagnetic spectrum is shown in Figure 1.

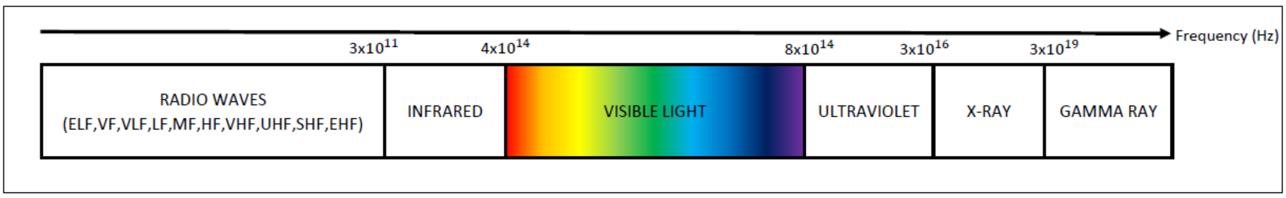

Figure 1. Electromagnetic wave spectrum

Radio frequencies can be used in many fields such as television broadcasting, mobile phone (GSM), satellite communication, radio broadcasting and global positioning systems (GPS). Spectrum on figure shows that 300 GHz bandwidth is available for that purpose. With the use of visible light communication, an area of approximately 400 THz will be put into service for communication systems. Visible light communication is crucial because of providing faster data transfer opportunity for more user. The strong attenuation of radio waves especially in underwater communications (Dimitrov and Haas, 2015), is a clear indication that VLC systems provide new capabilities in areas where radio waves are inadequate. The differences between VLC and RF system are shown in Table 1.

Table 1. Differences between VLC and RF

Property	VLC	RF
Wave Length	380 nm – 780 nm	1 mm - 10^5 mm
Bandwidth	Unlimited (~400 THz)	Regulated and Limited (~300 GHz)
Electromagnetic Interference	No	Yes
Signal	Real, Unipolar	Complex, Bipolar
Communication Range	Narrow	Wide
Line o Sight	Yes	No
Mobility	Limited	Good
Power Consumption	Low	Medium
Security	Good	Poor
Hazard	No	Yes
Installation	Easy	Medium

ACO-OFDM modulation technique which is a sub version of orthogonal frequency division multiplexing (OFDM) is used for this study. In this multicarrier technique ACO-OFDM, the signals generated for optical channel must be real. Subcarriers should have Hermitian symmetry for that purpose. Additionally, only odd subcarriers are used to send data symbols and even subcarriers are set to zero to avoid loss of performance as a result of clipping noise.

In the ACO-OFDM technique, data symbols are first divided into N/4 complex symbols for N subcarrier.

$$\boldsymbol{X_d} = [X_1 \; X_2 \; X_3 \; \dots \; X_{N/4}]^T \qquad (1)$$

Next, the data symbols should be put in Nx1 array form below in order have Hermitian symmetry.

$$\boldsymbol{X} = [0 \; X_1 \; 0 \; X_2 \; 0 \; \dots \; X_{N/4} \; 0 \; X_{N/4}^* \; 0 \dots \; 0 \; X_2^* \; 0 \; X_1^*]^T \qquad (2)$$

In this vector $(.)^*$ denotes conjugate and $(.)^T$ denotes transpose. After then, IFFT is applied to vector X to get vector x[n] in time domain. Cyclic prefix, that must have a length at least equal to the length of the multipath channel, is added to the array to eliminate intersymbol interference (ISI).

New studies on VLC are being carried out day by day and new researches are gained to the literature with these researches. There are many studies about different modulation types, different communication distances and different data rates.

Videv and Haas (2014) designed a VLC system by using space shift keying (SSK) modulation technique. There were more than one LED and photodiode pairs in the system. As the distance between LED and photodiode pair increased, symbol estimation performance was adversely affected.

Baranda et al. (2013) used software defined radio (SDR) in their receiver and transmitter designs. Also Thorlabs PDA36 was used as photodiode in the receiver design. The system is not an appropriate commercial design due to the high cost of SDR and photodiode.

Samudika et al. (2016) have successfully completed the transfer of audio files in MP3 and PCM (Pulse Amplitude Modulation) format at a distance of 20 cm with the system they have prepared. OOK (On-Off Keying) modulation type is used for the design. OOK is not appropriate modulation type because it does not support high data transfer rate.

Ding et al. (2013) designed a prototype with low cost components by using On-Off keying (OOK) modulation type. VLC system was implemented by using Universal Serial Bus (USB) interface. VLC - USB communication system prototype provided 2 Mbps data transfer rate.

Afgani et al. (2006) added a pilot signal for synchronization and they used white LED light source in the system. By using OFDM modulation, 8 kbps maximum data transfer speed was provided.

Islim et al. (2017) achieved 11.95 Gbps data transfer speed in their work by using the micro LED structure and OFDM modulation type.

Tsonev et al. (2015) emphasized that the data transfer speed can be increased up to 100 Gbps by using laser diodes and wavelength division multiple modulation type.

In this study, considering the information and deficiencies in the literature, a unique VLC system based on ARM was designed using low cost and commercial off-the-shelf components and using ACO-OFDM modulation algorithm that is intended the future works.

4. Method

The VLC system block diagram and test set-up that includes receiver and transmitter circuits is shown in Figure 2. In this system, data transfer is unidirectional between two RS-232 serial ports of a personal computer (PC). Two serial ports of PC are connected to the system, one for the transmitter circuit and the other one for the receiver circuit. The communication between circuits are provided by a software which is called VLC_TxRx_v0.5 and the software is written by using Visual Studio C#. The software can either send basic test commands or a loaded text document. The software sends given data to transmitter via serial port 1 and gets the data that is collected by receiver circut via serial port 2. After the transmission this software compares the original sent data and received data. Finally indicates that received byte count and the error rate. Figure 2 shows the main controller software interface and a sample data transmission. Receiver and transmitter circuits both have LPC1768 ARM Cortex M3 based microcontroller. The digital data that comes from the computer via software and serial port, is converted to analog signals by internal digital to analog converter (DAC) of the microcontroller. LED driver circuit applies the analog signal form to the LED light source and as a result the signals propagate in optical channel.

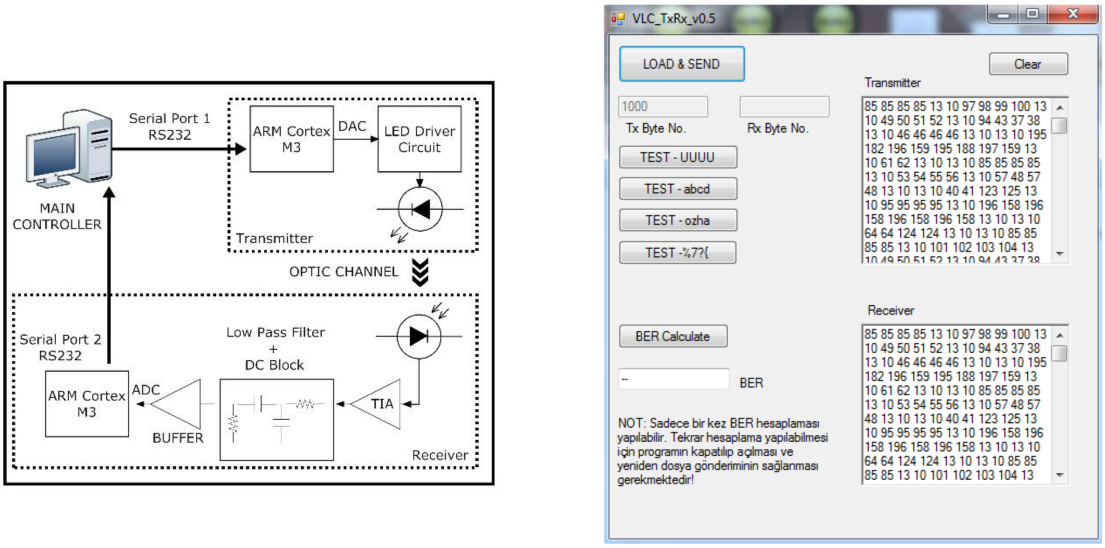

Figure 2. VLC system block diagram and test set-up (left), the main controller software interface (right)

Intensity modulated light signals are converted to electrical current signals by photodiode in the receiver circuit. Current signals are amplified and converted to voltage signals by using trans-impedance amplifier circuit. Next, the data signal is filtered by passive low pass filter and is sent to second amplifier circuit. The filtered clean signal is amplified by the second stage amplifier. At this point signal has no DC offset voltage anymore. Analog signals are converted to digital signals via analog-to-digital converter (ADC) circuit. In this context, LED driver and photodiode receiver circuits are shown below.

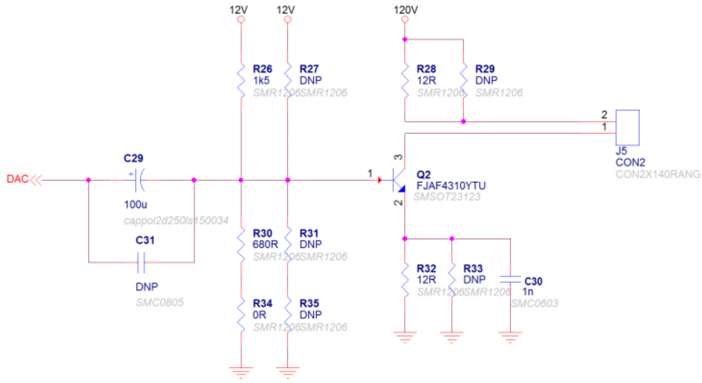

Figure 3. LED driver circuit

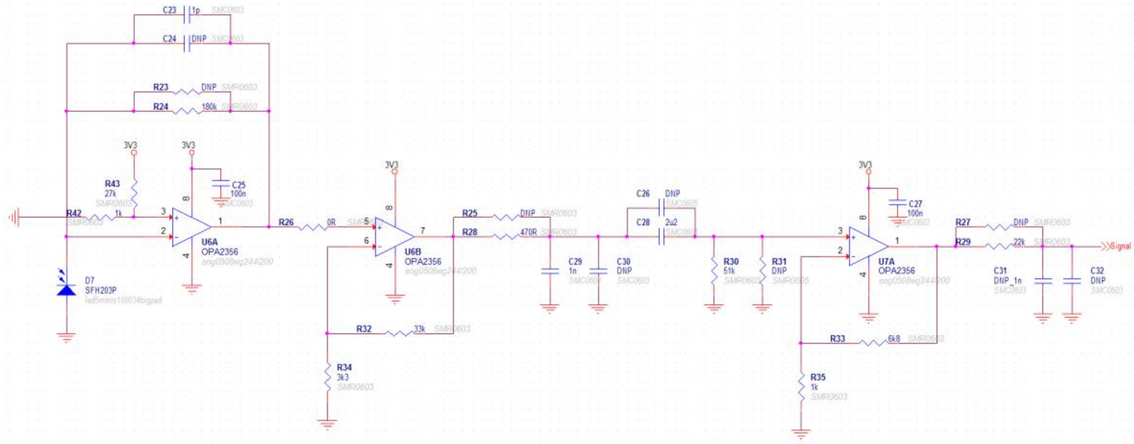

Figure 4. Receiver circuit

The analog signals are generated on the microcontroller by applying a number of signal processing algorithms to the binary message data that is expected to be transmitted. The algorithm processes including ACO-OFDM modulation and demodulation are described in the block diagram in Figure 5.

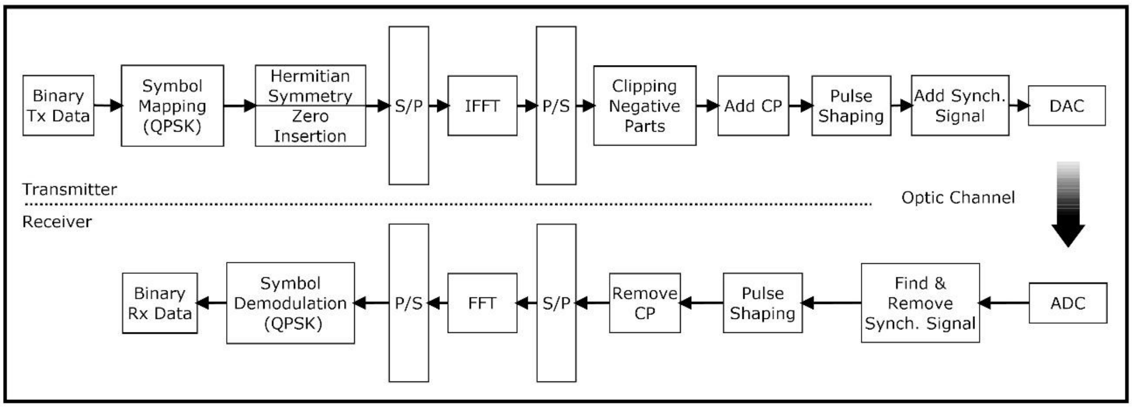

Figure 5. The block diagram of ACO-OFDM algorithm

Firstly, the binary data bits are changed into symbols by using quadrature phase shift keying (QPSK) symbol mapping. The system is configured to send 4-byte data packets. It means there will be totally 16 symbols after applying QPSK symbol mapping to 32-bit data. Various array operations are performed to ensure that the subcarriers have Hermitian symmetry which is essential to have real values after applying Inverse Fast Fourier Transform (IFFT). The complex data symbols are mapped onto Nx1 vector shown in Equation (2) by using their complex conjugate with sorted in reverse and by inserting zero between symbols. After that, the serial data is converted to its parallel form (S/P) and then IFFT is applied to obtain orthogonal subcarriers. In this point, negative values are clipped because intensity modulation of light can be performed by using only positive valued signals. In ACO-OFDM, only odd subcarriers contain data when even subcarriers are set to zero. It means the resulting real time signal will have a half-symmetry that is the first half of signal will be the same as the second half (Mesleh et al. 2012). Thus, clipping the negative values is performed without any loss of information. Cyclic prefix (CP) is added to the beginning of the signal to avoid intersymbol interference. Root raised cosine pulse shaping is applied to achieve an enhanced bandwidth. Next, a synchronization marker signal is added to easily locate the beginning of the transmitted signal. Finally, the digital data is converted to the corresponding analog form by using internal Digital to Analog Converter (DAC) unit of the microcontroller and sent to the receiver via the optical channel.

In receiver circuit whole algorithm is reversed to get original binary data. This time, the received analog signal at the output of the trans-impedance amplifier is converted to digital data by using Analog to Digital Converter (ADC) as the first step. Next, the synchronization signal is located and removed. The remaining signal is filtered by applying the same pulse shaping data and then the cyclic prefix is removed. The resulting serial data is converted to parallel form to apply Fast Fourier Transform (FFT). After that, the parallel data is converted to serial form (P/S) again and finally the original binary data is obtained by demodulating it.

In transmitter circuit design, it was preferred to use Class A type BJT amplifier circuit structure. Class A type BJT amplifier circuits are common emitter amplifiers and have very large voltage gain. Class A amplifier is always biased transistor circuit which means it conducts current whether the signal applied or not. Although this result is a disadvantage for amplifier circuits, we change it to an advantage by using this current as lighting source. FJAF4310 was used in amplifier circuit due to its proper high current and voltage characteristics. Also, OSRAM Classic-A Series 14 W LED was used as the light source. It provides 1521 lumen brightness and 6500 K color temperature. The powerful light source has 25 LED connected in series.

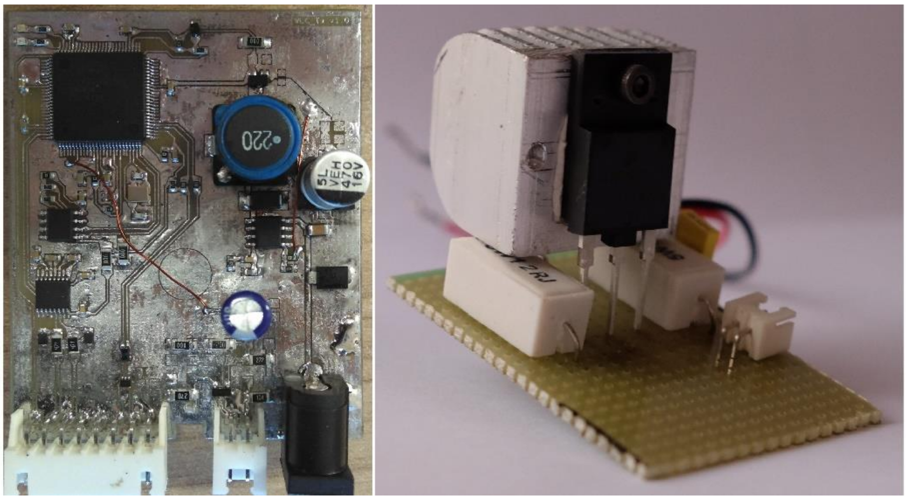

Figure 6. Transmitter controller circuit (left) and BJT amplifier circuit (right)

Figure 7. Transmitter design with aluminum enclosure

In receiver circuit, SFH203P photodiode was preferred to use which has large bandwidth, short switching time, very low dark current and very low capacitance. The trans-impedance and second stage amplifiers have operational amplifier circuits (OPAMP). OPA2356 high-speed, voltage-feedback CMOS operational amplifier was preferred due to proper frequency response and low input bias current characteristics. ADS7883 was used as an analog-to-digital converter which provides 12-bit resolution and 2 MHz sampling frequency.

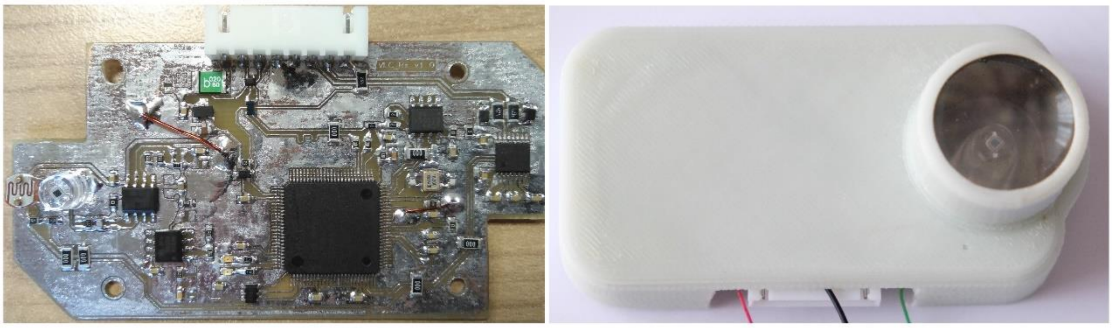

Figure 8. Photodiode receiver circuit and receiver enclosure printed by 3D printer

5. Experimental Results

To test system, arbitrary characters representing the message to be transmitted are sent to transmitter input via RS-232 interface using personal computer and serial Monitoring Software. ACO-OFDM applied signal which is created by microcontroller based VLC system is monitored with 100 MHz digital oscilloscope (INSTEK). As an example, four-bytes length 'UUUU' characters are transferred and generated ACO-OFDM signal is given at Figure 9 which includes a start and a synchronization signal. Total time duration of signal processing is measured as 2.44 milliseconds in transmitter and 3.8 milliseconds in receiver for transferring four-bytes length 'UUUU' message.

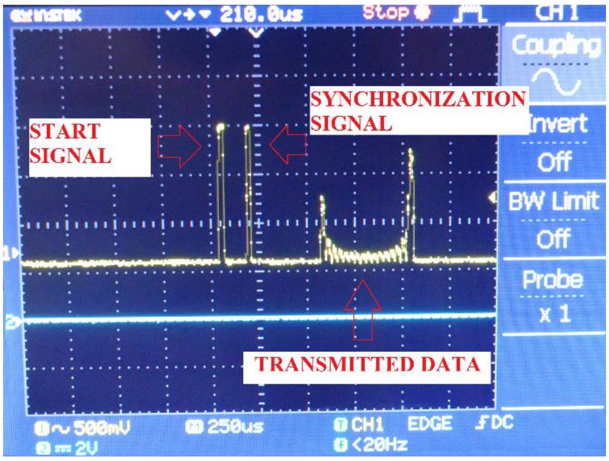

Figure 9. Transmitted 4 byte 'UUUU' data signal form

Three different test scenarios applied to measure the communication range. First, the light source and the photodiode receiver are placed against each other. At each step, light density at the receiver measured with a smart phone (HUAWEI NOVA) and third-party software. In y-axis test the distance between light source and photodiode is increased with staying opposite each other. In x-axis test, the photodiode is shifted only to right or left. The third test is circular axis test. In this test, the photodiode moves on a circular orbit that has the light source on the center shown in Figure 10.

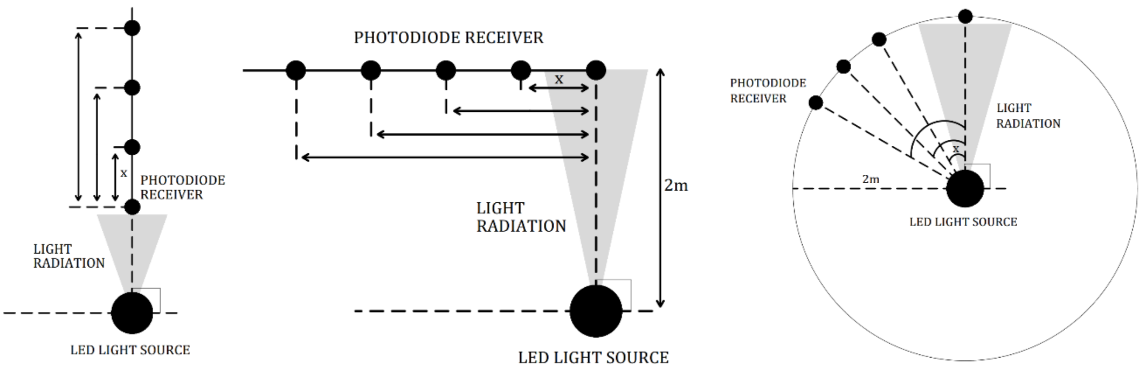

Figure 10. Y-axis test (left), X-axis test (center) and circular axis test (right)

The results of three stage tests applied to the designed VLC system are summarized on Table 2 below. The data transfer has been achieved error-free at a distance from 1.8 m to 3 m with a bit rate of 3.5 kbps. In addition, it has been observed that the system communicated up to 85 cm on the x-axis and up to 50° azimuthal angle. Again it can be clearly seen from Table 2 that below the certain light density (175 lux) the communication is interrupted. Incorrect characters received when the light density value is between 175 to 185 lux. Additionally the test results show the communication is interrupted when the light intensity is above 400 lux also. In the Y-axis test with 1.5 m distance, the system has no received signal. Actually the received signals are lost in overexposed light intensity because of the close distance. It means that the system can perform in a certain depth of field area.

Table 2. System test results

Test	Distance / Angle	Light Intensity	Error Rate (Bit/Byte)
Y- Axis Test	1.5 m	500 lux	No Communication
Y- Axis Test	1.8 – 3 m	370 – 185 lux	0/5000
Y- Axis Test	3.15 m	177 lux	84/5000
Y- Axis Test	3.3 m	160 lux	No Communication
X- Axis Test	0 – 0.85 m	300 – 205 lux	0/5000
X- Axis Test	1 m	175 lux	No Communication
Circular Axis Test	14° - 50.80°	310 - 215 lux	0/5000
Circular Axis Test	58.22°	175 lux	No Communication

The system test results show that designed multicarrier visible light communication system have mainly two important contributions for literature. Table 3 shows that the main advantages of the system compared to before researches.

Table 3. Designed VLC system contributions

Videv and Haas (2014) designed a system by using space shit keying (SSK) modulation and more than one LED – Photodiode pair.	We have developed a system by using multicarrier (ACO-OFDM) modulation which can provide more speed and more robust communication. In addition we have accomplished this by using just one LED – Photodiode pair.
Baranda et al. (2013) used software defined radio (SDR) and Thorlabs PDA36 which are not usefull for commercial purpose and so expensive.	We have developed a system by using low-cost and commercial off-the-shelf electronic components. Whole system circuits, enclosures and control software are designed by ourselves.
Samudika et al. (2016) used OOK modulation for transferring data at a distance 20 cm.	We have developed a system which can communicate at a distance 1.8 m to 3 m.
Ding et al. (2013) designed a system with low-cost components to use On-Off keying (OOK) modulation.	We have developed and realized a system with low-cost components to use multicarrier OFDM modulation.

6. Conclusion

Visible light communication system including a receiver and a transmitter circuit has been designed using ACO-OFDM modulation and signal processing algorithms implemented with ARM Cortex M3 based microcontroller. The data transfer has been achieved at a distance from 1.8 m to 3 m with a bit rate of 3.5 kbps. In addition, the system communicates up to 85 cm on the x-axis and up to 50° azimuthal angle. Measured light intensity indicates that under 175 lux and above 400 lux the communication is interrupted. It is shown that our design can be used for indoor lightening applications with standard ceiling height. Beside this, the system can be used for underwater and vehicle to vehicle communication which contains lightening and data transferring at the same time. Users can be use for example internet when sitting under the light or can be warned because of getting so close to another car much more than it should be when driving. We have developed an ARM based low cost prototype with low power consumption. Furthermore, our system is one of the few implementations that ACO-OFDM and signal processing algorithms are running on the microcontroller.

Conflict of Interest

No conflict of interest was declared by the authors.

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