

Performance improvement of visible light communication links based on coded unipolar OFDM

Wasnaa N. Al-Musawi, Hassan K. Al-Musawi

Department of Electronic and Communications Engineering, Faculty of Engineering, University of Kufa, Kufa, Iraq

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ABSTRACT

Visible light communications are limited by the narrow bandwidth of their sources as the light-emitting diodes, which restricts the high data rates transmission. A potential technique such as multi-carrier modulation is considered promising for achieving a high-speed data rate and enhancing system performance. This paper proposes turbo coding with unipolar orthogonal frequency-division multiplexing (U-OFDM) for indoor environments. The system under U-OFDM considerations can reduce the inter-symbol interference caused by multiple paths and mitigate burst errors by adopting an iterative turbo decoding. The system performance is evaluated regarding the bit error rate (BER) for the range of the signal-to-noise ratio (SNR) under receiver field-of-view (FOV) restriction. The obtained results show that the performance system of the target BER (below the threshold limit of 3.8×10^{-3}) has a power penalty of ~ 9 dB for modulation order of 64 for quadrature amplitude modulation scheme, FOV of 50° , and incidence angle of half power assigned to 30° . The obtained results also showed a ~ 10.8 dB improvement in the SNR when comparing the present system with coded-DC-biased optical OFDM under the same considerations.

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Corresponding Author:

Wasnaa N. Al-Musawi

Department of Electronic and Communications Engineering, Faculty of Engineering, University of Kufa
Kufa, Najaf Governorate, Iraq

Email: wasnaan.almusawi@student.uokufa.edu.iq

1. INTRODUCTION

At the present, the ever-increasing traffic transmitted by communication networks, especially wireless systems, can be noted continuously. Therefore, modern applications that require broadband increase the demand for broadband internet services. Due to the need for increased research, development, and the creation of new developing technologies, the need for wireless communication capacity is predicted to expand dramatically over the next several years [1]. The fifth-generation (5G) networks must enable extremely high user data rates (~ 10 Gbps or more) contrasted to the previous generation [2]. Visible light communication/light fidelity (VLC/LiFi) techniques may enable extremely high-speed data rate systems for interior scenarios, fulfilling the purpose of 5G network needs both outdoors and indoors, as a possible replacement for radio frequency (RF) congestion-based wireless communication [3], [4], see Figure 1. VLC technology is a specific term for a manner of wireless communication in which information is transmitted based on the modulation of light waves from the optical spectrum, which includes a range of wavelengths (380-750 nm) called the visible spectrum [5]. VLC offers many desirable features over its RF technology, including but not limited to the following: no electromagnetic interference (EMI), large spectrum, easy to install, low-cost, high-energy efficiency, information security, unlimited bandwidth, and health safety [6].

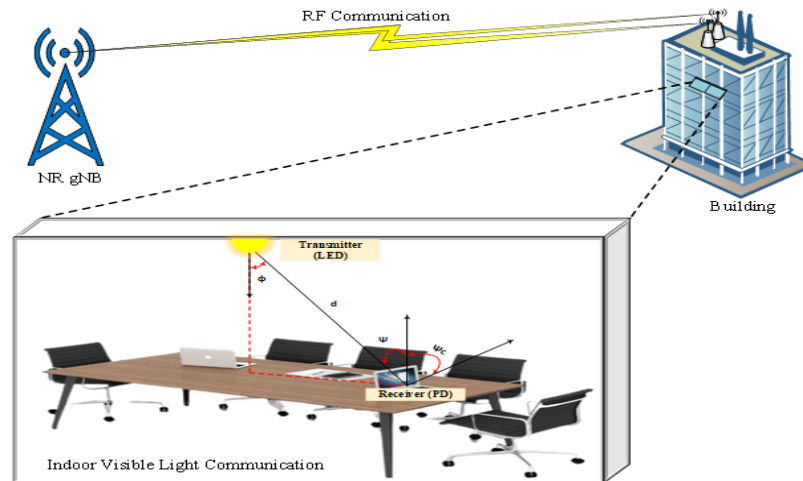


Figure 1. Hybrid 5G-VLC architecture

The concept of VLC relies on adopting the light-emitting diode (LED) to provide high-speed communication in addition to the lighting. However, white LEDs' modulation bandwidth is restricted to a few MHz owing to their lengthy luminous lifetime [7]. The optical orthogonal frequency-division multiplexing (O-OFDM) technology in VLC communication systems has been proposed and widely studied to address the problem of LED's limited bandwidth [6]. However, since VLC channels are frequency-selective, critical intersymbol interference (ISI) degrades system performance significantly. To address these problems, researchers have turned to O-OFDM approaches such as DC-biased optical OFDM (DCO-OFDM), unipolar-OFDM (U-OFDM), and asymmetrically clipped optical OFDM (ACO-OFDM) to reduce the ISI [8], [9], provide high-speed, and wide-bandwidth data transmission [6]. Two conditions constrain the O-OFDM signal: its amplitude must be real and positive because VLC systems use the intensity modulation/direct detection (IM/DD) approach [10]-[15]. To achieve the real condition in the three types of O-OFDM (ACO-OFDM, U-OFDM, and DCO-OFDM), the property of the Hermitian symmetry (HS) can be adopted before the process of inverse fast Fourier transformation (IFFT) to create a bipolar signal in DCO-OFDM, ACO-OFDM, and U-OFDM. The HS property sacrifices half of the number of subcarriers to provide a signal in real-time. Then, the output of the IFFT block is fed to a parallel-to-serial (P/S) converter and will be $X(k)$ at k -th time instant. DCO-OFDM adds DC bias after the IFFT procedure to solve the bipolarity problem [16], [17]. In contrast to DCO-OFDM, the addition of DC bias is removed using ACO-OFDM, which reduces its spectral efficiency in half.

U-OFDM achieves a superior BER and is more efficient than DCO-OFDM regarding power consumption, although at the cost of spectral efficiency [8], [16]. Single carrier modulation is usually used in optical systems because it is easy to implement and modify. Therefore, it is insufficient to fulfil the requirements of high-speed data transmission. To meet these needs, advanced methods that combine multi-carrier modulation and forward error correction (FEC) are good alternatives [18]. Koo *et al.* [19] used turbo codes combined with O-OFDM to VLC systems in indoor environments over a noisy optical channel. The first scheme reduces the known transmitter interference, while the second allows for high-speed data transmission. The performance of the turbo coded-O-OFDM (TC-O-OFDM) in the VLC system has been proposed in [20] to reduce errors caused by VLC channel impacts. The findings of [20] may be used to evaluate the required BER and the system's characteristics, such as field-of-view (FOV) limitation at the receiver, incidence angle, and transmitted power.

In this paper, a new technique that combines the turbo code with U-OFDM (TC-U-OFDM) in the VLC system is proposed to minimize channel effects, aiming to enhance the system performance regarding BER to mitigate errors caused by VLC channel impacts and the uncertainty inherent in channel parameter estimation. One type of O-OFDM was adopted, namely U-OFDM. The findings of the MATLABTM simulation show that the recommended turbo encoder and decoder are appropriate for the investigated VLC system to achieve the required BER and minimize information loss. As a result, the information's reliability will be guaranteed. The research findings can be utilized to assess the trade-off between the desired service quality and VLC characteristics, such as the limitation of the receiver's FOV and the semi-angle. The rest of the paper is arranged as follows: the VLC system model is introduced in the second section. The third section discusses the major suggested turbo-coded VLC system. Additionally, it explains the main suggested algorithm for turbo decoding with O-OFDM in the VLC system. In the fourth section, the numerical results of the MATLABTM

simulation are revealed and discussed, and eventually, the fifth section summarizes the conclusions of the research work.

2. VLC system model

The suggested TC-U-OFDM system has three components: the transmitter (Tx), the optical channel, and the receiver (Rx) as described in Figure 2. A turbo encoder with a specific length (packet length) is used to encode the binary bit stream (as arranged in non-return to zero (NRZ)). Then, the coded bits $X_c(m)$ produced by the encoder block are transferred into 64-quadrature amplitude modulation (64-QAM) symbols $X(m)$ with serial-to-parallel (S/P) conversion prior to their application to the block OFDM scheme, where $m = 0, 1, \dots, k-1$ is the index of the subcarriers, and k is the fast Fourier transform (FFT) size ($k = 1024$).

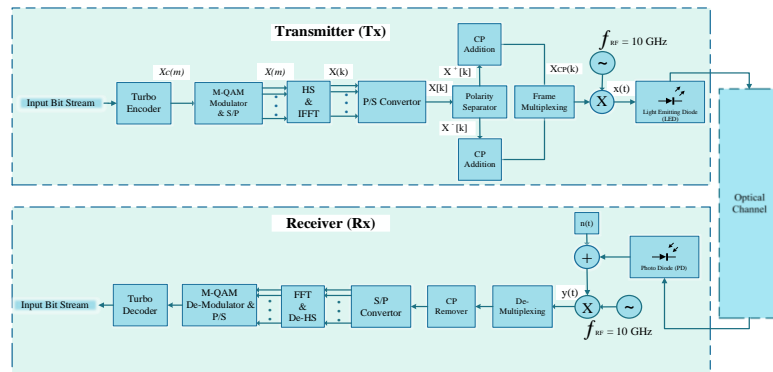


Figure 2. General block diagram of turbo-coded VLC system

In the U-OFDM block, after HS and IFFT application, the positive and negative parts of the real bipolar signal $X(k)$ generated by the IFFT process are broadcast in two different frames separately. The signal with positive polarity is broadcast in the first frame as positive frame $X^+(k)$, whereas the signal with inverted polarity is conveyed in the second frame as the negative frame $X^-(k)$, and cyclic prefix (CP) is added to each frame due to communication is via a frequency-selective channel. In contrast, the negative frame $X^-(k)$ is delayed and then transmitted after the $X^+(k)$. Finally, the real, non-negative signal is utilized to drive the optical source represented by the LED.

At the optical channel part, the Barry *et al.* proposed line-of-sight (LOS) channel model [21] is adopted for VLC links among numerous channel models proposed in the literature. Typically, LOS wireless systems have a greater power efficiency since the LOS path dominates, and the reflected paths' power is significantly lower [6], [22]. The following assumptions are included in the suggested channel model: First, the light propagation environment is considered to be indoors, with no barriers between the source and destination; second, the power that comes from the direct path is greater than the power of the light path that reflects to the receiver from the ceiling and walls. The considered indoor VLC system with the LOS channel model is shown in Figure 1. The DC channel gain that is being examined is represented as (1) [22]-[25]:

$$H(0) = \begin{cases} \frac{A_r(m+1)}{2\pi d^2} \cos^m(\phi) g(\Psi) \cos(\Psi) & 0 \leq \Psi \leq \Psi_c \\ 0, & \text{elsewhere} \end{cases} \quad (1)$$

where, m is the Lambertian order, which is expressed as (2) and (3):

$$m = -\frac{\ln 2}{\ln \cos(\phi_{1/2})} \quad (2)$$

$$g(\Psi) = \begin{cases} \frac{n^2}{\sin^2(\Psi_c)}, & 0 \leq \Psi \leq \Psi_c \\ 0, & \text{elsewhere} \end{cases} \quad (3)$$

where A is the size of the photodetector's light-sensitive region in m^2 , Ψ is the irradiance angle, ϕ is the incidence angle, d is the distance between the LED and photodiode (PD), $g(\Psi)$ is the concentrator's gain, Ψ_c is the FOV of the receiver, $\phi_{1/2}$ is the incidence angle of half LED power (semi-angle), and n is the refractive

index. It is possible to describe an IM/DD optical wireless communication system in Figure 3. Assume $x(t)$, $h(t)$, and $n(t)$ is the transmitted signal, impulse response of the channel, and the component of the additive white gaussian noise (AWGN), respectively. Then, the corresponding received signal $y(t)$ can be described as [6].

$$y(t) = h(t) \otimes x(t) + n(t) \tag{4}$$

At the receiver side, after the optical signal is received by the PD, the reconstructed signal $y(t)$ is sent to the S/P block, CP removal block, fast Fourier transform (FFT), and P/S converter.

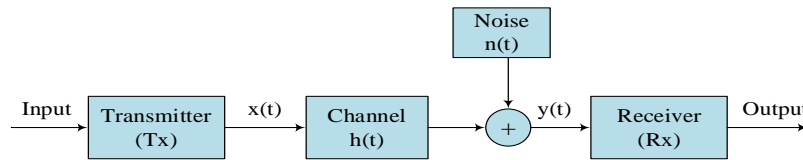


Figure 3. Channel model of baseband communication system

3. CODED-OPTICAL OFDM

The performance of the VLC channel has been impacted by a many of characteristics that affect the whole performance of the system. The change in the incidence angle may indicate a gradual change in distance. Subsequently, the distance influences the signal-to-noise ratio (SNR). The optical concentrator focuses the light beam into a narrow PD region, and this action will reduce the receiver’s FOV field. Hence, the bandwidth and SNR of the system will be improved [22], [26]. Angles of incidence and irradiance considerably affect the VLC system’s performance. Due to increasing the incidence angle, beam divergence is produced and consequently a lower value of power at the receiver, resulting in a lower SNR. Finally, if a beam does not arrive inside the FOV region (or semi-angle), its influence on the overall received power is negligible, resulting in communication failure; hence, the semi-angle of the transmitter and the FOV of the receiver are crucial system parameters. Improper selection of the above parameters can also lead to an impairment in the power of the received signal, where the noise level of the system may increase. Furthermore, inaccurate estimation of VLC parameters causes degraded system performance. In this work, the turbo encoder and decoder are applied to make the system adaptable against these VLC channel limitations. The suggested turbo decoder’s general structure is shown in Figure 4.

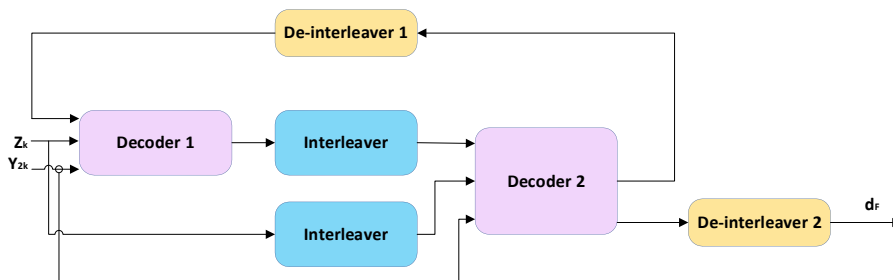


Figure 4. General structure of turbo decoder

In the receiver side, two soft decoders exchange soft data across numerous iterations. Turbo decoders use multiple decoding algorithms such as an a posteriori probability (APP) and maximum a posterior probability (MAP). However, with the development of turbo codes in 1993, the APP became the primary representation of the soft-input soft-output (SISO) algorithms for generating probability information on trellis code symbols [27]. In this research, the APP decoding algorithm is adopted to accomplish the SISO implementation required for iterative decoding in this system, according to [28], [29]. The APP algorithm aims is to compute APPs on the encoded symbols and the information bits. The APP algorithm of the input bitstream d and codeword $X_c(m)$ can be represented as (5) and (6) [27], [30]:

$$P_r = \{d_t = t \mid y_1^T\} = \sum_{e \mid d(e)=d} \alpha_{t-1}(S^s(e)) \gamma_t(e) \beta_t(S^e(e)) \tag{5}$$

$$P_r = \{Xc_t = Xc \mid y_1^T\} = \sum_{e|Xc(e)=Xc} \alpha_{t-1}(S^s(e))\gamma_t(e)\beta_t(S^e(e)) \tag{6}$$

where $\alpha(\cdot)$, $\beta(\cdot)$, γ , S_t, y_1^T , and e is the forward path metric, backword path metric, transition or branch metric, the state at time t , the received bitstream from $t=1$ to $t=\tau$, and the edge of the code terllis respectively. To limit the effect of numerous parameters that characterize the VLC channel, an adaptive BER reduction strategy employing a combination of the VLC system and a turbo decoder is proposed. The complexity and BER performance of a turbo decoder are significantly affected by the number of iterations and the packet length.

4. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation results of the proposed coded-VLC indoor system performance are introduced with reasonable discussion. In order to reduce the burst errors caused by VLC channel impacts and the unpredictability of estimating channel parameters, the TC-U-OFDM in IM/DD systems has been investigated. The numerical findings of a TC-U-OFDM system in an indoor scenario over a LOS VLC channel are presented in this section. Table 1 offers the key parameters used to simulate the proposed system.

Parameter	Value
FFT size	1024
Typical room dimensions	(5×5×3) m ³
Carrier frequency	10 GHz
Frame length	125000
Interleaver type	Random
Coding rate	1/3
Modulation scheme	64-QAM
Data rate	1 Gbps
Decoding algorithm	APP
FOV angle	50°
$\phi_{1/2}$	30°
Distance	2.15 m
Refractive index	1.5
LED power	20 mW
PD's responsivity	1

The performance of the turbo coded-VLC system is simulated utilizing MATLAB™ software. The BER performance against the SNR of the back-to-back (B2B) of the U-OFDM scheme with and without turbo code is shown in Figure 5 for five iterations. It can be seen that at low SNR values, the iterative decoding is more effective compared to the high SNR levels. The proposed TC-U-OFDM approach achieves the required BER (below the FEC limit of 3.8×10^{-3}) at an SNR value of ~ 7.5 dB. So, the fourth iteration is selected in the rest of the simulations because it is consumed less delay time than iteration 5.

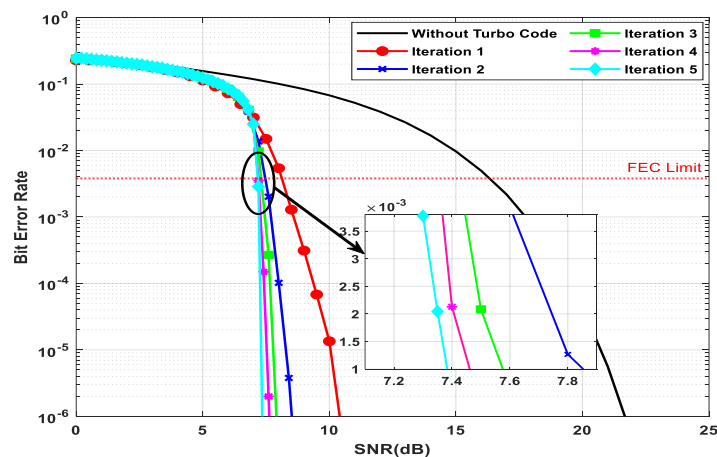


Figure 5. Comparison between the proposed TC-U-OFDM and the conventional U-OFDM systems regarding BER and SNR for M=64

The comparison between the proposed TC-U-OFDM and the conventional U-OFDM systems regarding BER and electrical SNR with different receiver FOVs is offered in Figure 6. It observed that larger FOVs present worse performance than narrower FOVs under the FEC limit. As illustrated in Table 2, the TC-U-OFDM approach achieves the desired BER even with larger values of FOV with iterative decoding of 4.

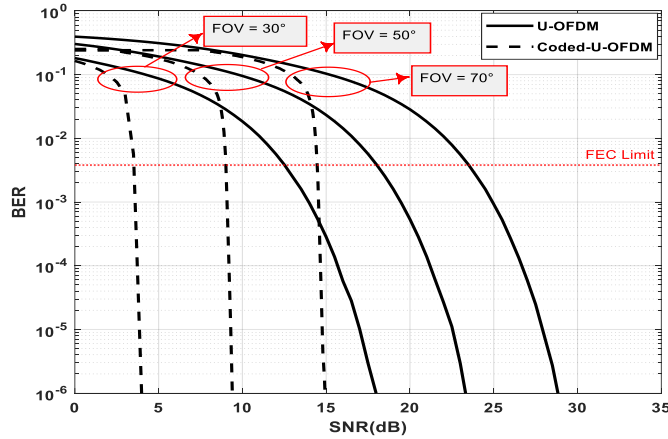


Figure 6. Comparison between the proposed TC-U-OFDM and the conventional U-OFDM systems regarding BER and SNR with different receiver FOVs, M=64

Table 2. SNR improvements of TC-U-OFDM over traditional U-OFDM for different FOVs

FOV angles	SNR (dB) without coding	SNR (dB) with coding
30°	12.528	3.522
50°	18.026	9.014
70°	23.511	14.461

Figure 7 depicts the system performance of the presented scheme in terms of BER versus the range of the SNR for iteration 4 and M=64. It can be seen that with the use of the turbo decoder scheme with four iterations, the overall system performance is improved. For instance, the power penalty of ~10.8 dB at the FEC limit for turbo-coded-DC-biased OFDM (TC-DCO-OFDM) compared to the coded-U-OFDM system at FOV of 50° and semi-angle of 30°.

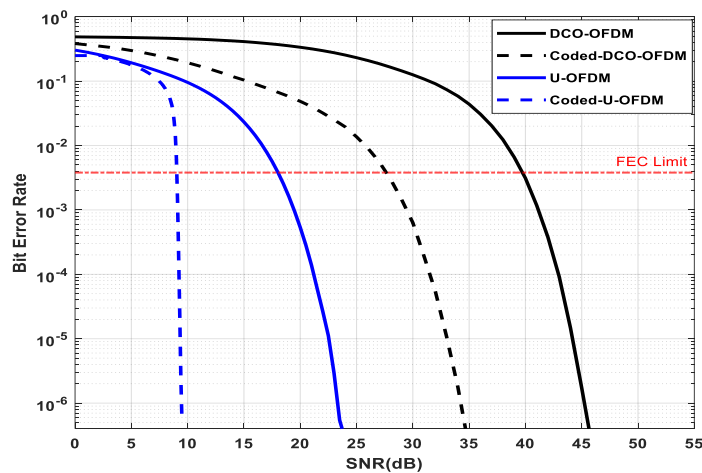


Figure 7. Comparison between the proposed TC-U-OFDM and the TC-DCO-OFDM systems in terms of BER and SNE for $\phi_{1/2}=30^\circ$, FOV=50°, M=64

5. CONCLUSION

In this paper, the TC-U-OFDM scheme based-VLC system was simulated and tested under LOS channel considerations. Many parameters may affect the optical channel in an indoor environment, such as the FOV of the receiver, transmitted power, incidence angle of half power, and the distance. The performance of the system was evaluated in terms of BER for the range of the receiver's FOV. The key findings showed that the performance system of the target BER versus SNR has a power penalty of ~9 dB for 64-QAM, FOV of 50°, and semi-angle of 30°. Moreover, the proposed model improved the SNR by ~10.8 dB compared to the TC-DCO-OFDM. The simulation results showed that adopting turbo code with U-OFDM can increase the reliability of the data transmission.




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BIOGRAPHIES OF AUTHORS



Wasnaa N. Al-Musawi    is received the B.Eng. degree in the Department of Electronic and Communication Engineering, Kufa University, Najaf, Iraq, in 2018. She is currently an M.Sc. student in the last stage at the Department of Electronic and Communication Engineering, Kufa University, Najaf, Iraq. Her current research interests are in the area of optical communication, and visible light communication systems. She can be contacted at email: wasnaa.n.almusawi@gmail.com.



Hassan K. Al-Musawi    received a Bachelor's degree in Electrical and Electronic Engineering from the University of Technology in Baghdad, Iraq in 1998, starting a career as a consultant engineer at the University of Kufa, Iraq for Electrical projects development. He received the M.Sc. degree with distinction in Optoelectronic and Communication Engineering from Northumbria University at Newcastle, U.K. in 2010, then he worked as an assistant lecturer in the Faculty of Engineering, University of Kufa, Najaf, Iraq. He received the Ph.D. degree in the Radio-over-Fibre (RoF) and Radio-over-Free Space Optics (RoFSO) for the indoor and outdoor communication systems in the Optical Communication Research Group at Northumbria University, U.K. in 2017. He is currently working as a lecturer at the Department of Electronics and Communications, University of Kufa. Hassan K. Al-Musawi becomes a Member (M) of IEEE in 2014 and he is a technical committee member at several international conferences and journals. He serves as a review board member for several international journals and conferences. He also presented his research at several conferences and events. Finally, his research interests include the area of optical wireless communications, free-space optics, visible light communications, hybrid radio and optical wireless communications. In addition to the mobile communication systems including fifth-generation (5G) technology. His contact email: hasank.baqir@uokufa.edu.iq.