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An Adaptive Turbo Coded-OFDM Scheme for Visible Light Communications

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Abstract—In visible light communications (VLC) the main bottleneck is the limited bandwidth of the light emitting diodes, which limits the maximum transmission data rates. Multicarrier modulation schemes are one possible option to increase the data rate as well as improve the link performance. In this paper, we present the turbo coded orthogonal frequency-division multiplexing (OFDM) scheme to mitigate interference and noise as well as to remove multipath induced inter symbol interference in a VLC system. Simulation results are used to compare the performance of the proposed system compared to classical optical OFDM schemes of DC-biased optical and asymmetrically clipped optical-OFDM. The results presented may be used to investigate the interaction between VLC system parameters (e.g., receiver field-of-view limitation, incident angle, light emitting diode power) and the bit error rate performance of the soft turbo decoder.

Index Terms—Visible light communications, adaptive turbo code, OFDM, optical wireless communications.

I. INTRODUCTION

Visible light communications (VLC) plays an important role in recent wireless optical communication systems. This is mainly due to several interesting features of improved energy efficiency, license-free, wide bandwidth, immunity to the radio frequency (RF) induced electromagnetic interference and a low cost backhaul [1], [2]. However, the low modulation bandwidth of light emitting diodes (i.e., a few MHz for standard LEDs) is a major issue in VLC systems since it limits the maximum transmission data rates. There are a number of options that could be employed to address this problem including multi-carrier modulation schemes such as orthogonal frequency-division multiplexing (OFDM) and multi-band carrier-less amplitude and phase (m-CAP) modulation [3], [4], [5]. Among these, OFDM is widely-adopted in VLC systems, which offers improved spectral efficiency, mitigation of multipath induced inter-symbol-interference (ISI) and fading [6], [7], [8].

In OFDM, the requirement for a high peak-to-average power ratio (PAPR) is seen a disadvantage in both RF and VLC communication systems due to the non-linearity of the power amplifier and the LED, respectively. In [6], the authors have demonstrated that the high PAPR in OFDM can be constructively exploited in intensity modulation/direct detection (IM/DD) VLC systems. In [7], a novel IM/DD VLC system based on a hybrid asymmetrically clipped optical

OFDM (ACO-OFDM) and ON-OFF keying (OOK) modulation scheme was reported. The latter system combines ACO-OFDM and OOK modulation schemes, while the signals can be recovered at the receiver to support different quality of service with high spectral efficiency and can be adapted to various receivers with different complexities. In [8], a new receiver based on the minimum mean-square error criterion for ACO-OFDM, which used all the subcarriers to improve the link bit error rate (BER) performance significantly, was reported.

In this paper, we investigate turbo coded-OFDM in IM/DD VLC system in order to mitigate errors occur duo to VLC channel influences and uncertainty of estimating channel parameters. At the transmitter, we use two well-known optical OFDM signaling of i) ACO-OFDM; and ii) DC-biased optical OFDM (DCO-OFDM). Monte- Carlo simulation results confirm the suitability of the proposed turbo-transceiver for the considered VLC system in terms of achievable target BER that the system need to work efficiently. Results presented may be used to evaluate the trade-off between the required quality of service in terms of the BER and VLC parameters such as receiver the field-of-view (FOV) limitation, incident angle and LED power.

The rest of the paper is organized as follows. In Section II, the system model and our main assumptions are presented. Section III describes the main proposed algorithm of turbo-coded OFDM in VLC system. Finally in Section IV, simulation results and discussion are provided and finally, Section V concludes the paper.

II. SYSTEM MODEL

The general structure of the proposed turbo coded OFDM-based VLC system is depicted in Fig. 1. As shown, the independent pseudo-random binary sequence (PRBS) $d_d(t)$ in the non-return to zero (NRZ) format of length 100 is encoded using a parallel concatenated turbo encoder and generated interleaved encoded bits are then mapped onto the quadrature phase shift key (QPSK) constellation symbols $x_{QPSK}(t)$ s prior to being applied to the OFDM block. The number of OFDM subcarriers are set to 128. Subsequently, the DC biased OFDM signal is used for IM of LEDs for transmission over the free-space channel. Since OFDM is a complex bipolar signal,

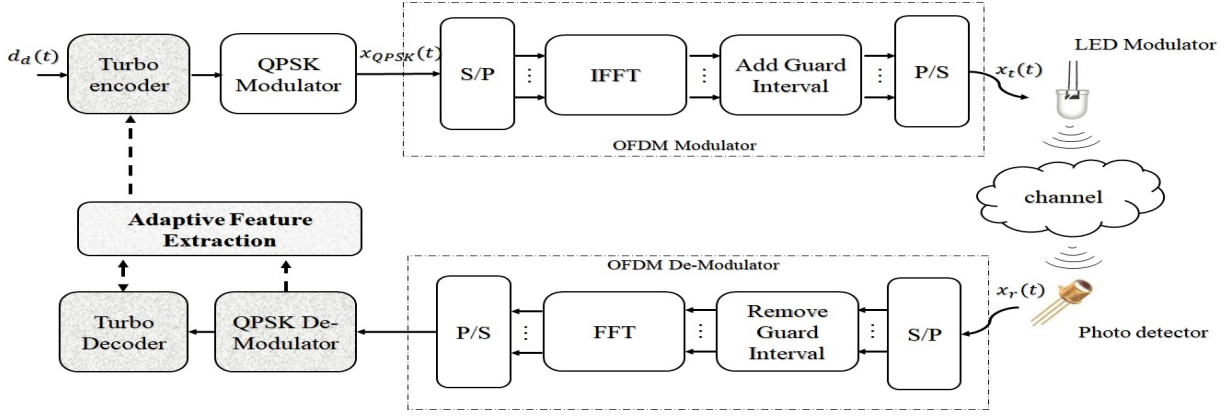


Fig. 1. Block diagram of turbo encoded optical OFDM system.

it is modified to meet the requirement of IM/DD VLC systems where the signal must be real and unipolar. Thus, both DCO-OFDM and ACO-OFDM are proposed as the modified version of optical OFDM [9]. In DCO-OFDM, a DC bias is added and hard clipping is performed whereas in ACO-OFDM only the odd subcarriers are utilized to convey the information and clipping is applied to make the OFDM signal positive.

At the receiver side, after optical detection, the regenerated OFDM signal is passed through the serial to parallel converter, guard interval removal, fast Fourier transform (FFT) and parallel to series modules, respectively. After removing the guard interval, the frequency domain received signal corresponding to the k -th subcarrier ($k = 1, \dots, 128$) can be expressed as [10]:

$$X_r[k] = \mu X_t[k] H[k] + W[k], \quad (1)$$

where $X_r[k]$, $X_t[k]$, $H[k]$ and $W[k]$ are the received signal, transmitted signal, complex channel coefficient, and additive white Gaussian noise (AWGN) corresponding to the k -th subcarrier, respectively. The receiver responsivity factor μ represents the conversion ratio between received optical power and photodiode current. Here, we assume a vehicular system where the receiver is "mobile". The time/frequency selectivity of the channel is due to the motion of the receiver [15]. Hence, we can assume that $H[k]$ is different for each subcarrier. To prevent burst errors due to the frequency selective channel, the demodulated signal is applied to the *turbo decoder*, which uses the *maximum-a-posteriori* (MAP) criterion as described in Section III, in order to regenerate the estimated version of the transmitted data stream.

Among several channel models proposed for VLC links in the literature, we choose the line of sight (LOS) channel model proposed by Kahn and Barry [11] which is depicted in Fig. 2. The adopted channel model implies the following assumptions: **i)** we assume the indoor propagation environment, where we have no obstacles between the transmitter and the receiver; **ii)** the power of the diffused light (i.e., reflection on the ceiling or walls) reaching the receiver is weaker than the power received from the direct LOS path. The considered channel DC gain is

expressed as [11]:

$$H(0) = \begin{cases} \frac{(m+1)A}{2\pi d^2} (\cos \phi)^m T_s(\psi) g(\psi) \cos(\psi), & 0 \leq \psi \leq \psi_c \\ 0, & \psi > \psi_c \end{cases} \quad (2)$$

where m is the order of *Lambertian* emission expressed as:

$$m = -\ln 2 / \ln(\cos \phi_{1/2}), \quad (3)$$

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2 \psi_c}, & 0 \leq \psi \leq \psi_c \\ 0, & \psi > \psi_c \end{cases} \quad (4)$$

where d being the distance from transmitter to receiver in meter, A the size of the light-sensitive area of the photo detector (PD) in m^2 , ϕ the angle of incidence, ψ the angle of irradiance, $T_s(\psi)$ the signal transmission of the filter, $g(\psi)$ the gain of the concentrator, ψ_c the FOV at the receiver, n the refractive index and $\phi_{1/2}$ the semi-angle at half luminance of the LED.

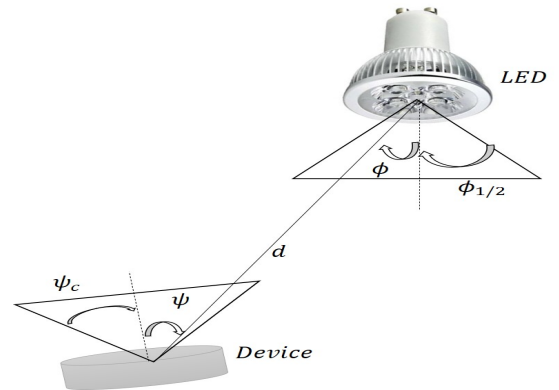


Fig. 2. Configuration of the transmitted and received beams in the considered LOS channel model.

III. ADAPTIVE TURBO CODED OPTICAL OFDM

As discussed in the previous section, the VLC channel depends on several parameters which affect the overall system

performance. In what follows, we provide more details about these parameters (i.e., d , A , ϕ , ψ , receiver FOV and $\phi_{1/2}$).

d may affect performance in two different ways. First, when the receiver is not tilted, the height is fixed and only the distance is changed and hence, the incident angle increases as the distance increases. So, when the distance is gradually changing, this can be characterized by the transition of the incidence angle. Second, by changing the distance, the signal-to-noise-ratio (SNR) is altered. For an improved performance, it is suggested to use a PD with wider surface area. However, increasing the optical gain of the element reduces its FOV. We can employ an optical concentrator to avoid this. Note, at the receiver an optical concentrator can be used to focus the optical beam on to a small area PD, thus leading to improved bandwidth (i.e., reduced capacitance in PD) and higher SNR [12].

The incidence (ϕ) and the irradiance (ψ) angles have also a major impact on the performance of VLC systems. Increasing ϕ leads to beam spreading (i.e., larger illumination area at the receiver plan) and therefore reduced received power level at the PD, thus lower SNR. Similarly, the received power decreases with the increase of ψ , thus confirming *Lambertian* emission pattern of the LED. Finally, the receiver FOV and the semi-angle of the LED are key parameters because if a ray does not reach within the FOV (or $\phi_{1/2}$), its effect on the total received power is not considered and this characterizes a link fail.

As a matter of fact, it is of practical importance to investigate the impact of the aforementioned parameters on the SNR and on the overall performance of the system. Inappropriate selection of the aforementioned parameters can degrade the received signal power and increase the noise level of the system. Besides, imperfect estimation of VLC parameters leads to performance degradation. To make the system robust to these VLC channel impairments, we make use of turbo coding and turbo decoding in our considered VLC system. The general structure of the proposed adaptive turbo decoder is depicted in Fig. 3. The receiver is composed of two soft decoders that exchange soft information (extrinsic) through several iterations. There are three main decoding algorithms used within decoders to implement the soft-input, soft-output processing needed for iterative decoding, namely MAP, log-MAP and max-log-MAP algorithm. In this paper we make use of log-MAP algorithm since the overall performance of log-MAP decoding scheme is better than the other two decoding schemes [13], [14].

An adaptive BER minimization algorithm is introduced in combination with a turbo decoder to overcome the impact of different parameters, which characterize the VLC channel. In a turbo decoder, two parameters namely the number of iteration and the block size, play an important role in the overall BER performance and complexity of the decoding algorithm. As we observe from Fig. 3, the *adaptive feature extraction* block is added to control the performance of the turbo-coded system by changing these two parameters. The general procedure of the latter block is described in what follows.

Algorithm 1 Pseudo-Code of the Adaptive Turbo Receiver

```

1: Set:
   FOV = 50°
    $\psi < \text{FOV}$ 
    $\phi_{1/2} = 30^\circ$ 
    $\phi < \phi_{1/2}$ 
2: Initialize:
   Block_length = 100
   Sample data of length 500 bits
   BER_target
3: for num_iteration = 1 to 5 do
4:   Start encoding the sample data
5:   Digitally modulate the encoded data
6:   Modulate data using LED & send through VLC channel
7:   Receive optical data and demodulate
8:   Start decoding
9:   Calculate BER
10:  if BER > BER_target then
11:    Update parameters according to
       block_length = block_length + 10
12:  else
13:    break
14:  end if
15: end for

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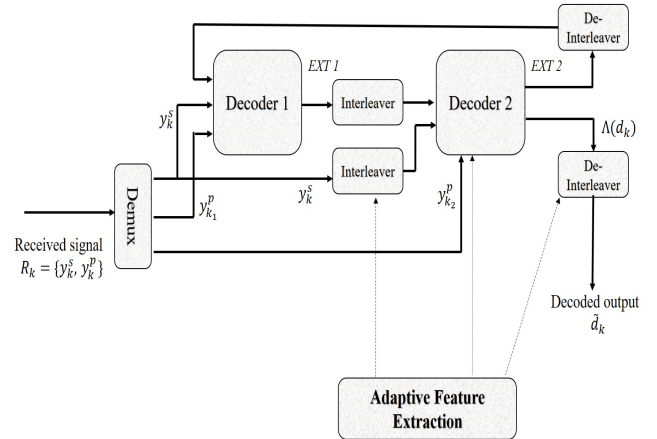


Fig. 3. Configuration of the considered adaptive turbo decoder.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we provide numerical results to evaluate the performance achieved by the turbo-coded optical OFDM system over a LOS VLC channel in an indoor environment. Parameters used throughout simulations are given in Table I.

The BER performance of turbo coded optical OFDM is simulated using MATLAB. Figure 4 shows the BER performance of conventional OFDM, DCO-OFDM and ACO-OFDM over a LOS VLC channel with and without turbo coding for different angles of incident. We observe a significant BER improvement using turbo code. Moreover, as the incident angle becomes larger, the system performance degrades progressively and for a FOV angle greater than 50° , the link is totally interrupted. It can be seen that ACO-OFDM performs slightly better than DCO-OFDM. Although conventional OFDM has the lowest

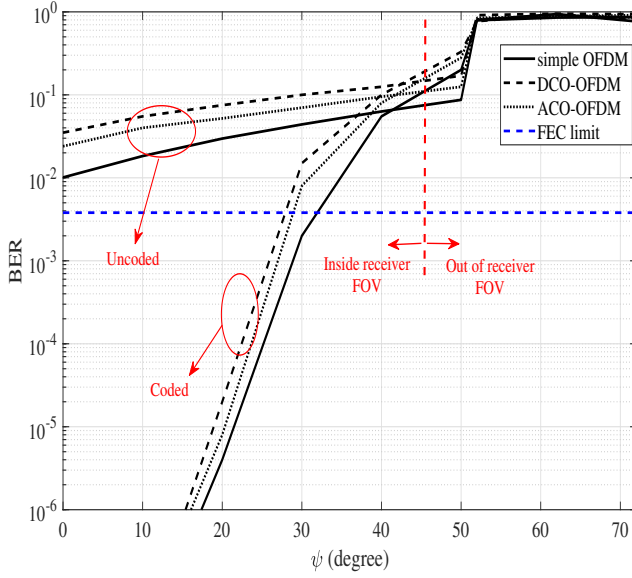


Fig. 4. BER performance of the turbo coded VLC system with respect to different incident angles, receiver FOV = 50°, $\phi_{1/2}$ = 30°, LED power = 0.5 W and d = 1.5 m.

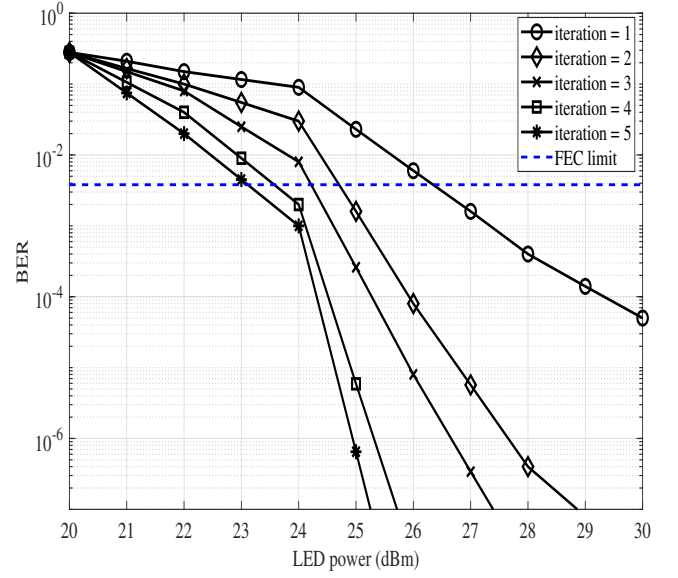


Fig. 5. BER performance of the turbo coded VLC system versus LED power, receiver FOV = 50°, $\phi_{1/2}$ = 30°, and d = 1.5 m.

TABLE I
PARAMETERS USED THROUGHOUT SIMULATION

Parameter	Value
FOV angle	50°
$\phi_{1/2}$	30°
LED power	0.5 W
d	1.5 m
Turbo code rate	1/3
Modulation type	QPSK
FFT size	128
Decoder type	max-log MAP

BER, it can not be directly applied to optical OFDM systems and hence, the modified ACO-OFDM is adopted.

Figure 5 shows the BER performance of turbo coded ACO-OFDM scheme versus the LED power spanning from 0.1 to 1.1 W for different number of decoding iterations. Obviously, the overall BER performance is improved by increasing the number of iterations. However, iterative decoding with larger LED power benefits more from the turbo effect than lower LED power. For instance, at a BER of 10^{-4} , which is well below the forward error correction (FEC) limit of 3.8×10^{-3} , the power penalties are respectively 0.2, 1, 1.6, and 5 dB for iteration numbers of 4, 3, 2 and 1 compared to the iteration number of 5.

Finally, Fig. 6 illustrates the BER performance of DCO and ACO-OFDM against the energy to noise ratio of (E_b/N_0) for a range of FOVs. Notice that, FOV is a crucial parameter for determining the capturing range of the receiver. We observe that, narrower FOVs leads to lower BER performance than wider FOVs. However, we also observe that, even with wide FOVs, the proposed turbo coded scheme achieves the target BER at relatively low values (i.e., < 8 dB) of E_b/N_0 .

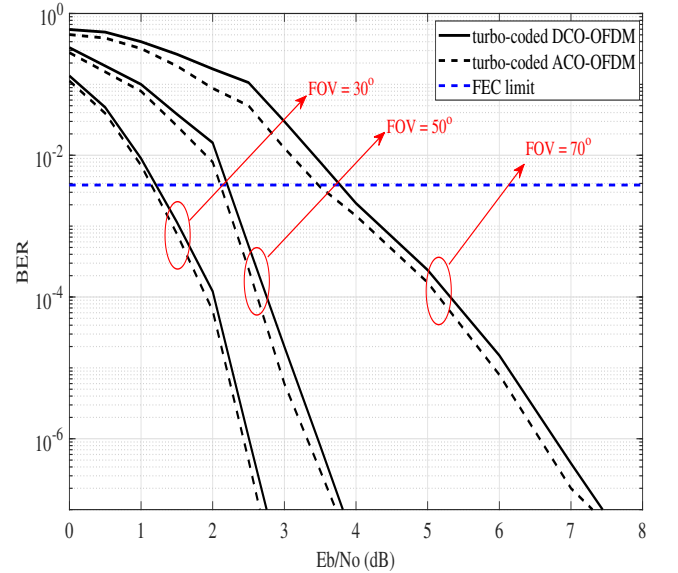


Fig. 6. BER performance of the turbo coded VLC system with different receiver FOVs, LED power = 0.5 W and d = 1.5 m.

V. CONCLUSION

In this paper, we focused on improving the reliability of data communication in a VLC channel by using an adaptive turbo coded-OFDM scheme. We considered both DCO and ACO-OFDM signaling. Our numerical results indicated that DCO-OFDM is suboptimal in terms of BER in both uncoded and turbo-coded configurations and confirmed the adequacy of ACO-OFDM. The limit of the incident angle with respect to the receiver FOV was also characterized to determine the link interruption limit. The improvement brought by the turbo decoder was shown to be dependent on the LED power or

equivalently on the distance separating the LED and the PD.

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