Int. J. Electron. Commun. (AEÜ) 84 (2018) 111–122

Contents lists available at ScienceDirect

Int. J. Electron. Commun. (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

Channel estimation in ACO-OFDM employing different transforms for VLC

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ARTICLE INFO

Keywords:
Visible Light Communication (VLC)
Discrete Hartley Transform (DHT)
Hadamard Coded Modulation (HCM)
Fast-Walsh Hadamard Transform (FWHT)
Channel Estimation
CRLB

ABSTRACT

The pronounced eminency of assuring simultaneous illumination and communication has driven Visible Light Communication (VLC) to gain significant ubiquity in recent times. This paper proposes comb type pilot arrangement based channel estimation for Asymmetrically Clipped Optical OFDM (ACO-OFDM) and different multicarrier transmission systems like Discrete Hartley Transform (DHT)-based ACO-OFDM and Fast-Walsh Hadamard transform (FWHT)-based Hadamard Coded Modulation (HCM) over dispersive VLC channel. Various channel estimation algorithms like Least Square (LS), Minimum Mean Square Error (MMSE), and Interpolation techniques namely Linear, Spline, and Low-Pass are evaluated and compared for the aforesaid systems employing different orders of constellation. Here, an elaborate mathematical analysis is accomplished and Cramer Rao Lower Bound (CRLB) is derived for the channel estimation error. Simulated results emphasize that, ACO-OFDM and DHT-based ACO-OFDM have improved Bit Error Rate (BER) performance than HCM at lower Signal to Noise Ratio (SNR), while at higher SNRs HCM dominates the former. Furthermore, the simulated results evidences that, in all multicarrier systems MMSE algorithm has reducible probability of error than LS because, at higher SNRs LS is more susceptible to noise and Spline Interpolation outperforms both LS and MMSE. The simulated results are validated analytically demonstrating good agreement.

1. Introduction

The substantial enhancement in the acquisition of mobile devices such as smart phones, palmtops, laptops, wearable devices and many other new devices which are on the Internet-of-Things (IoT) are driving an unquenchable demand for data access over the wireless networks. This enormous demand to transmit information wirelessly at a rapid pace and accurately with high throughput necessitates to overuse the existing radio frequency (RF) spectrum making it to become as one of the scarcest resource in the near future. This even manifests as contention and interference, which results in increase in latency and decrease in network throughput. To alleviate this problem, alternative communications like Optical Wireless Communication (OWC) have evolved. OWC employing cost-effective devices such as light emitting diodes (LEDs) has given rise to a novel technology called Visible Light Communication (VLC).

VLC is referred to as short range OWC, utilizing light as a medium to transmit data rather than the RF carrier signal. The salient feature of this technology is that it offers huge, wide, unlicensed and unregulated bandwidth to enable seamless integration of multimedia services for indoor applications. In addition to it, the omnipresence of LEDs has enabled solid state lighting to revolutionize the indoor illumination where, the current incandescent and fluorescent lamps have been replaced by the LEDs at a rapid pace [1]. This is due to the fact that, LEDs offer several distinguished advantages such as longer life expectancy, low power consumption, high tolerance to humidity, and no electromagnetic interference.

Aiding to this, the main advantage of LEDs are they are capable of switching to different light intensities which are imperceptible by the human eye [2,3]. VLC utilizes this prominent nature of the LED to transmit data by intensity modulating LEDs at a faster rate to facilitate high data rate communication. Toshihiko et al. considered the basic properties of LEDs for simulating an optical channel and showed how this channel model is suitable for indoor communication [4]. This beneficial nature of VLC of assuring simultaneous illumination and communication has driven it to be amalgamated for many Smart city applications. In [5], the authors briefed about the significance of usage of VLC in vehicular communication highlighting the illumination requirements.

In spite of possessing several advantages, the drawback of LED is its limited modulation bandwidth which makes VLC to rely on modulation formats which are efficient in terms of power, spectral and computational analysis in order to guarantee high-data rate communication. The significant contrast between RF and VLC is that in VLC, the data is encoded by varying the intensity of the emitted light wave which is referred to as intensity modulation (IM) and the demodulation is

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https://doi.org/10.1016/j.aeue.2017.11.016
Received 4 July 2017; Accepted 17 November 2017

referred to as direct detection (DD) at the receiving end where a photodetector is employed. Hence, the modulation formats must be compatible with IM/DD systems.

A brief summary on the PHY layer implementation of the IEEE 802.15.7 standard for Short-Range Wireless Optical Communication using Visible Light is presented in [6]. Here, issues that drove the technical content which includes the single carrier modulation formats such as ON–OFF keying, Pulse Width Modulation (PWM), Variable Pulse Position modulation (VPPM) were discussed. However, when the data rates are increased their performance deteriorates due to Inter Symbol Interference (ISI). In addition, due to dispersive nature of the optical wireless channel they rely on complex equalizers at the receiving end. With the advent of time, multiple carrier modulation (MCM) techniques such as Orthogonal Frequency Division Multiplexing (OFDM) which is considered as a radical technology for RF was included for OWC.

OFDM is a high dimensional MCM technique which facilitates high data rate transmission due to its inherent nature of being resilient to frequency selective fading channel environment, combating ISI, etc. In the literature, hardware prototype for physical layer implementation of a VLC system based on a modified version of OFDM modulation technique is provided in [7]. When OFDM is used in RF wireless system, the complex baseband OFDM signal is used to modulate the amplitude and phase of the RF carrier [8,9]. In case of IM/DD systems the baseband signal modulates the intensity of the optical carrier not its amplitude or phase [10]. It is mandatory for the signal which is to be transmitted to be both real and unipolar (positive). Firstly, in order to yield a real signal, the input to the Inverse Fast Fourier Transform (IFFT) block is constrained to satisfy hermitian symmetry criteria in a conventional OFDM system. But this involves additional complexity in the implementation and at the same time leads to spectral inefficiency as all of the subcarriers are not utilized for transmission of data.

For the purpose of obtaining a real valued signal, investigations were carried out on other multicarrier modulation techniques where, transformations such as Discrete Hartley Transform (DHT), Wavelet Packet Division Multiplexing (WPDM) and Hadamard Coded Modulation (HCM) have been considered for VLC. DHT being an invertible real trigonometric transform, DHT based multicarrier modulation format does not require hermitian symmetry and can carry twice the data compared to hermitian symmetry imposed IFFT. In [11], the performance of optical OFDM has been evaluated by incorporating DHT over AWGN channel. In this work, we have incorporated this transform to evaluate the system performance over dispersive VLC channel.

While, WPDM employs wavelet orthogonal basis functions for symbol modulation where, the basis functions are wavelet packet functions of finite length [12]. Similar to OFDM, WPDM also ensures orthogonality among the subcarriers. WPDM was proposed for VLC in [12], where the numerical result analysis shows advantages than conventional DC-Biased Optical OFDM (DCO-OFDM) in terms of superior out-of-band power leakage suppression, small Peak to Average Power Ratio (PAPR) and its robustness to channel dispersion. Hadamard Coded Modulation (HCM) based on fast Walsh Hadamard Transform (FWHT) was proposed as an alternative technique to FFT. It is well known that Hadamard matrices and the Hadamard transforms have been proposed as a precoder in OFDM systems to reduce PAPR. In [13], this technique is shown to attain a better performance for high average optical power scenarios because of its small PAPR.

The primary purpose of replacing FFT by these real transforms is to attain an increase in spectral efficiency as well to obtain a real signal fulfilling the requirements of IM/DD systems. Secondly, for making this real and bipolar signal as unipolar, several variants of OFDM were proposed in the literature out of which DCO-OFDM is the earliest variant. DCO-OFDM consists of adding a large DC bias to the bipolar signal to make it positive. However, the addition of DC bias makes this scheme as power inefficient. Hence, as a power efficient scheme Asymmetrically Clipped Optical OFDM (ACO-OFDM) is proposed where only odd subcarriers are modulated and the output signal is clipped at zero without the need of DC bias [14–16].

Since VLC channel is dispersive, sensing and tracking of this channel is essential for ensuring perfect reception of the transmitted data. From [17,18] it is evident that, wireless channel estimation can be performed by employing comb type pilot arrangement based channel estimation where, the pilot tones are inserted within a specific period into each OFDM symbol. This type of channel estimation incorporates different algorithms like Least Square (LS) and Minimum Mean Square Error (MMSE) to estimate the channel at the pilot frequencies followed by interpolating the channel.

Once, the channel information at pilot carriers are known then the channel state at the data subcarriers can be estimated by utilizing various interpolation techniques like Linear, Spline and Low-Pass. In [19], the authors carried out channel estimation using LS algorithm for DCO-OFDM and in [20] Interpolation based channel estimation was incorporated for ACO-OFDM. In either of the scenarios multicarrier transmission techniques and performance metrics such as power efficiency and spectral efficiency were not considered. Moreover, the result analysis in [19,20] depicts the power inefficiency as an *SNR* of 45–60 dB is required to achieve a reducible error floor.

The contribution of this work is to evaluate the performance of various multicarrier transmission systems like hermitian symmetry imposed FFT based-ACO-OFDM, DHT-based ACO-OFDM and HCM which is based on FWHT over dispersive VLC channel environment. In this work, the developed systems are analyzed and compared by taking into consideration comb type pilot arrangement based channel estimation algorithms like LS, MMSE and Interpolation schemes namely Linear, Spline and Low-Pass Interpolation over VLC channel as well as Additive White Gaussian Noise (AWGN) channel employing M-ary phase shift keying (M-PSK), M-ary quadrature amplitude modulation (M-QAM) and M-ary pulse amplitude modulation (M-PAM).

Even though, WPDM is shown to achieve better performance than DCO-OFDM in [12], it unveils that this technique involves an addition of DC bias to yield a real and unipolar signal which leads to power inefficiency. Hence, the result analysis depicts that it requires higher *SNRs* to achieve a reducible error probability. So, in this work we have focused on power efficient ACO-OFDM rather than DCO-OFDM. Furthermore, hermitian symmetry imposed FFT-based ACO-OFDM and DHT-based ACO-OFDM systems were compared with WPDM, HCM and DCO-OFDM systems in order to confirm the power inefficiency of DCO-OFDM. In addition, analytical expressions were provided to validate the simulated results. An elaborate mathematical analysis is carried out deriving the Cramer Rao Lower Bound (CRLB) for the channel estimation error.

The rest of the paper is organized as follows. Section 2 details the propagation characteristics of the Channel Model for VLC. Section 3 elaborates the mathematical analysis for the system models proposed along with the comparison of ACO-OFDM with DCO-OFDM and emphasizes the need of DHT, WPDM and HCM to attain spectral efficiency. Section 4 describes the mathematical analysis for various channel estimation techniques such as LS, MMSE and Interpolation. Section 5 derives the CRLB for the channel estimation error. Section 6 represents the results and discussions of this work. Finally, in Section 7 conclusions are drawn.

2. Channel model

A suitable channel model is essential to describe the propagation characteristics of visible light. There are certain parameters which are very much essential to model the channel. A simple work environment setup is considered with dimensions $6 \times 6 \times 3\ \text{m}^3$. The propagation characteristics are shown in Fig. 1. Since, there are LED's installed on the ceiling of the room hence from each LED there will be a Line-of-sight (LOS) component and additionally there are Non-Line-of-sight