# Efficient signalling technique for free space optics using auto-correlation OFDM

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***Abstract*— This document develops auto-correlated optical OFDM as a frame- work to implement OFDM on optical intensity channels. The drawbacks of conventional methods are mitigated in auto-correlated optical OFDM. Contrary to ACO-OFDM and DC-biased OFDM, the proposed technique uses all the available bandwidth for data modulation and does not require reserved subcarriers. Simulation results verify that auto-correlated optical OFDM has gain in Bit Error Rate as compared to conventional optical OFDM schemes.**

***Keywords*—VCC, OFDM, VLC.**

## 1. Introduction

Wireless optical technology provides various outdoor and indoor services such as indoor wireless infrared communications, terrestrial links , wireless ultraviolet communications , and Free Space Optics . The latter case uses visible light (wavelengths of 380-750 nanometres) as the medium for data transmissions. In this case, an additional advantage lies in the potential for simultaneous use of light for illumination and data communication termed Free Space Optics (FSO).

Solid state lighting (SSL) refers to a type of lighting that uses semiconductor light emitting diodes (LEDs) as a source of illumination rather than electrical filaments (used in incandescent halogen light bulbs) or plasma (used in fluorescent lamps). Recent developments in LED technology are paving the way towards its full adoption as a replacement to incandescent and fluorescent lighting and white LEDs are now considered as future lighting solutions. Sales of inefficient incandescent light bulbs will be outlawed in Ontario and California beginning in 2012. Australia has announced a similar ban beginning in 2010 and inefficient incandescent bulbs are no longer in Europe as of 2009. Surveys compare LEDs versus incandescent light bulbs and fluorescent lamps in terms of lifetime, efficiency, reliability and cost. One of the main advantages of LEDs over other lighting methods is their longer lifetime expectancy. The average life span of an LED is about 60 kilo hours which is considerably more than average lifetime expectancy of incandescent bulbs (about 1200 hours).

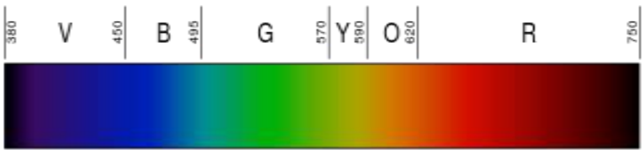


Figure 1.1: The visible spectrum corresponding to: 380-450 nm violet, 450-495 nm blue, 495-570 nm green, 570-590 nm yellow, 590-620 nm orange, and 620-750 nm red regionAnd fluorescent lamps (about 10 kilo hours). Other than that, LEDs are considered more energy efficient as they only consume about 6 W, which is 10% of the power used by incandescent bulbs (about 60 W), and 40% of that used by fluorescent lamps (about 14 W) per unit of light generated (lumen [lm]).Although the cost of a single LED bulb is more than an incandescent bulb or a fluorescent lamp (approximately $16 for LEDs made by STARLIGHT INC. compared to $1.25 and $3 for incandescent and fluorescents respectively ), the total cost of employing LEDs in terms of operating hours and installations is much less than employing other two methods. For example, if the electricity cost is estimated about $0.2 per kWh, the total cost of employing LEDs for 60 kilo hours operation is estimated around $88 which is considerably less than that for incandescent lights ($783) and fluorescent lamps ($186) . As a result, LEDs are more economical for lighting purposes. Fluorescent lamps contain toxic mercury that can be released if broken. Both incandescent light bulbs and fluorescent lamps suffer from their sensitivity to low temperatures and humid weathers. Hence, LEDs have less environmental impact and higher reliability in comparison to incandescent bulbs and fluorescents. However, the efficiency with which LEDs produce light degrades with heating effects. Further-more, the LEDs' brightness is limited per LED and sufficient number of LEDs is required for brightness of the area.

Apart from lighting advantages, LEDs can be modulated at rates greater than several hundred thousand times that of incandescent or fluorescent sources and hence offer the potential for data communication concurrent with lighting

 

## 2. Background

## 2.1 Basic Channel Properties

### 2.1.1 IM/DD Channels

Similar to other wireless optical communication systems, FSO relies on intensity modulation and direct detection (IM/DD) for data transmission. Figure 2.1 displays a block diagram of an intensity modulated direct detection system. The instantaneous optical intensity, I (t), is modulated proportional to the input electrical current x (t). This method of modulation is termed as intensity modulation and can be done by a laser diode (LD) or a light-emitting diode (LED). Usually, LEDs have higher reliability, lower cost and are considered more eye-safe compared to laser diodes. However, the main advantage of laser diodes is their higher speed of operation.

After data modulation, the intensity signal is transmitted through the channel. At the receiver, a photodiode is used to detect the received intensity. This method of detection is termed as direct detection.

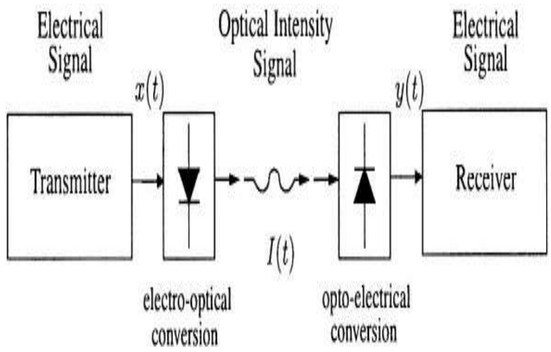


**Figure 2.1: A block diagram of an intensity modulated direct detection channel**

### 2.1.2 Photodiodes

Photodiodes are solid-state devices that are used to perform the optical to electrical conversion. They produce an output electrical current, y (t), proportional to the received intensity signal. The received current is then processed to extract the transmitted information. The key parameter in photodiodes is the responsively defined as,

$$R = \frac{Ip}{Pp}$$

Where $I_p$ is the average photocurrent generated and Pp is the incident optical power. The photodiode responsively depends on the physical structure of the photodiode and has the units of ampere per watt. Two common photodiodes that are currently used in practice are p-i-n photodiodes and avalanche photodiodes. The first type has lower cost but lower modulation bandwidth.

### 2.1.3 LED Characterization

A light-emitting diode (LED) is a semiconductor light source. Two important lighting factors of LEDs are color rendering index and luminous efficacy. The color rendering index is a measure of the ability of the LED to produce color in comparison with an ideal light source. The luminous efficacy on the other hand, is the measure of the efficiency with which the source produces visible light from electricity. It is equal to the ratio of luminous flux, to the total electric power consumed by the source. Therefore it has the units of lumen per watt. The LEDs produce white light suitable for illumination and data modulation. There are two popular methods to produce white light.

### 2.1.4 RGB LEDs

A simple way to form white light is to mix red, green and blue (RGB) colors with appropriate portions as shown in Fig. 2.2. The LEDs produced in this way are often referred to as RGB LEDs.

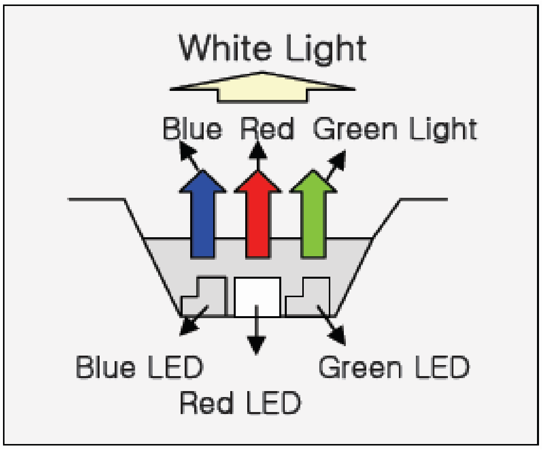


**Figure 2.2: The structure of RGB white LEDs**

### 2.1.5 Phosphor-based LEDs

This method involves coating a blue LED with a yellow emitting phosphor as shown in Fig. 2.3. The resulting LEDs are termed as phosphor-based white LEDs.

Phosphor-based LEDs have a lower luminous efficacy compared to RGB LEDs due to phosphor-related degradation issues. However, the majority of white LEDs that are currently in use on the market are manufactured using this technology. Apart from the advantage of requiring only a single color source, these types of LEDs are easier to design and are less expensive than complex RGB LEDs. Furthermore, the available modulation bandwidth of such LEDs can be enhanced by at least an order of magnitude using blue filtering. Due to the long decaying time of the phosphor, the modulation bandwidth of the white emission is limited to ~ 2 MHz.

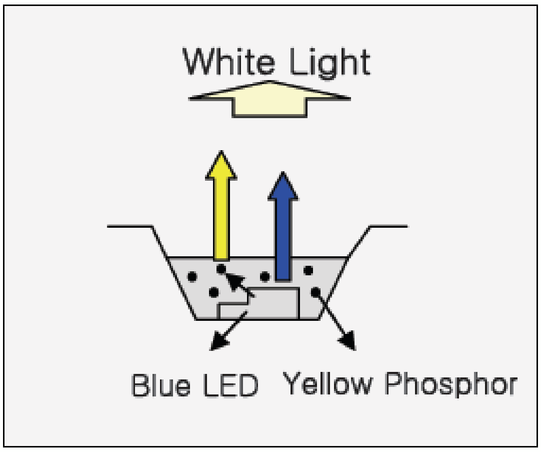


**Figure 2.3: The structure of phosphor-based white LEDs**

## 2.2 Compatible VLC signalling schemes

As discussed earlier in this Chapter, the modulated electrical amplitudes must satisfy the non-negativity constraint of IM/DD channels. This constraint does not permit direct application of conventional electrical modulations on IM/DD channels. A compatible modulation technique for such channels is on-off keying (OOK) modulation.

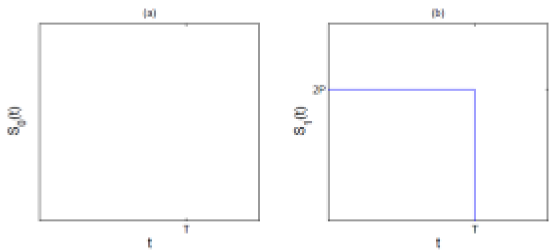


**Figure 2.4: NRZ OOK modulation technique: (a) denoting binary zero, and (b) denoting binary one.**

### 2.2.1 Orthogonal Frequency Division Multiplexing

Orthogonal frequency division multiplexing (OFDM) is an attractive multiple subcarrier modulation scheme which has widely been employed both in wireless and cable digital communications.

Some cable applications of OFDM include asymmetric digital subcarrier line (ADSL), very-high-bit rate digital subcarrier line (VDSL), power line communication (PLC), and multimedia over coax alliance (MoCA) home networking. Some notable OFDM wireless applications involve wireless local area network (WLAN) radio inter-faces (IEEE 8.2.11a, g, n), the terrestrial digital TV systems, the terrestrial mobile TV systems, and the wireless personal area network (PAN) ultra wide-band (IEEE802.15.3a)

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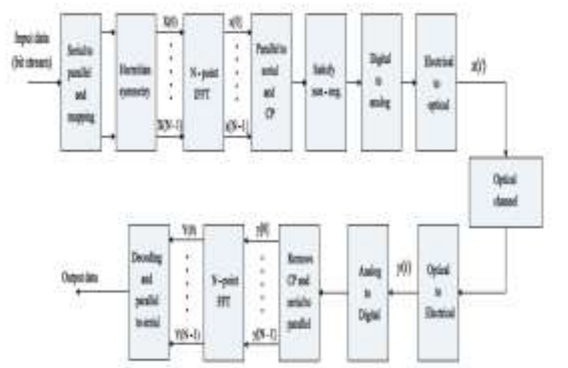

**Figure 2.5: Block diagram of an optical wireless system using OFDM**

## 2.3 Compatible OFDM schemes for IM/DD channels

As discussed earlier in this chapter, the amplitude non-negativity constraint of VLC channels does not allow direct implementation of OFDM on such channels. Several techniques have been proposed to ensure the non-negativity of the OFDM signal such as : DC-biased OFDM (DCB-OFDM) and Asymmetrically Clipped Optical OFDM (ACO-OFDM). These methods and their properties are explicitly presented in the following.

### 2.3.1 DC-biased OFDM

As discussed in Chapter 1, OFDM signals are in general bipolar signals and have both negative and positive amplitudes. One common method that can be used to guarantee non-negativity of the transmitted signal is to add a DC bias to the bipolar OFDM. The required DC bias to satisfy non-negativity is equal to the maximum negative amplitude of the OFDM signal.

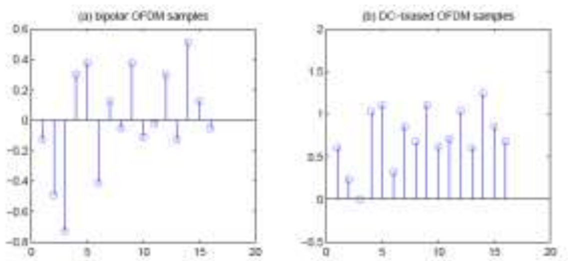

**Figure 2.6: Fig. (a) Shows bipolar OFDM time samples, Fig. (b) shows the DC- biased OFDM samples generated after adding a DC-bias to the bipolar samples in (a).**

 

## 3. Methodology

### 3.1 System Design

In Auto-correlated optical OFDM, the autocorrelation of frequency coefficients in (3.12) is used to produce unipolar signals directly without constraining the modulation bandwidth. In particular, the subcarrier amplitudes are chosen such that they form an autocorrelation sequence, which was shown in Sec. 3.1.2 To be necessary and sufficient to guarantee amplitude positivity. The autocorrelation sequences are generated by sub- optimally designing their z-plane zeros.

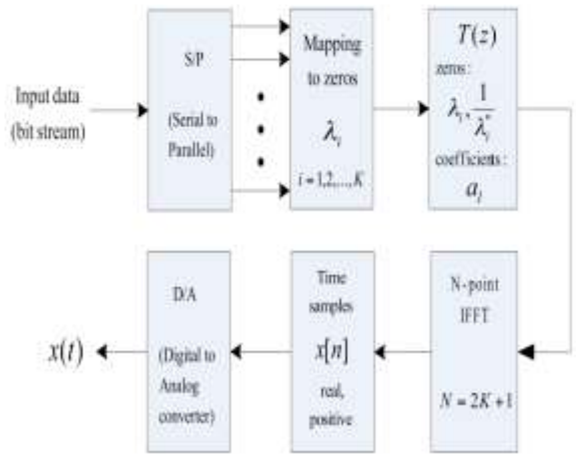


**Figure 3.1: Block diagram of the Auto-correlated optical OFDM transmitter**

Figure 3.1 shows a simple block diagram of the Auto-correlated optical OFDM transmitter. The input serial data is partitioned into parallel blocks which are mapped to the zeros of S (z) which lie outside the unit circle, i.e., λi. The characteristic z-domain function

$$T(z) = S(z)\ S^*\left(\frac{1}{z^*}\right)$$

Is then formed with conjugate reciprocal pair zeros λi and $1/\lambda_i^*$ to generate the autocorrelation coefficients al. Performing an N = 2K + 1 point IDFT on the coefficients of T (z) produces a positive time sequence x[n]. Finally, a positive OFDM signal x (t) which contains one period of the periodic signal in time is generated using the time samples x[n].

## 4. Experimental result

### 4.1 System configuration and parameters

At the beginning of this simulation MATLAB program, a script file OFDM_parameters.m is invoked, which initializes all required OFDM parameters and program variables to start the simulation. Some variables are entered by the user. The rest are either fixed or derived from the user-input and fixed variables. The user input variables include:

1) Input file - an jpeg image file (*.jpg) preferably of the size (448 x 336);
2) IFFT size - an integer of a power of two;
3) Number of carriers - not greater than [(IFFT size)/2 – 2];
4) Modulation Method - Auto-correlated optical OFDM, DC-biased OFDM, ACO-OFDM;
5) Signal peak power clipping in dB;
6) Signal-to-Noise Ratio in dB.

### 4.2 Simulation

**Table 1: Parameters for Simulation in Appendix B.**

| Parameter | Values |
|---|---|
| Source Image Size | 448x336 |
| No of sub-carriers | 1024 |
| No of Bits | 500 |
| Modulation method | Auto-correlated optical OFDM |
| Amplitude Clipping(dB) | 5 |
| Signal to Noise ratio(dB) | 10 |

there is a BER of 0.216903% while the percent error in the output image pixels is 0.628455%. This is expected when we are using Auto-correlated optical OFDM as the modulation technique. However the transmission and the reception time for Auto-correlated optical OFDM is quite high.

#### 4.2.1 Simulation for DC-biased OFDM

Parameters given in Table 2 are being considered for the simulation of DC-biased OFDM.

**Table 2: Parameters for Simulation of DC-biased OFDM**

| Parameter | Values | | | | |
|---|---|---|---|---|---|
| Source Image Size | 448x336 | | | | |
| No of sub-carriers | 1024 | | | | |
| No of Bits | 500 | | | | |
| Modulation method | DC-biased OFDM | | | | |
| Amplitude Clipping(dB) | 0 | 0 | 3 | 5 | 7 |
| Signal to Noise ratio(dB) | 0 | 3 | 5 | 7 | 10 |

For each set of amplitude clipping and Signal to Noise ratio, BER and the percentage error in the received image pixels are been calculated and tabulated in Table 3. Also the required transmitting and received time is being mentioned in the table.
The original image to be transmitted is shown in the Figure 4.1.

**Figure 4 .1: Original Image**

**Figure 4.2: Received Image of DC-biased OFDM (Amplitude Clipping=0dB & SNR=0dB)**

**Figure 4.3: Received Image of DC-biased OFDM**
(Amplitude Clipping=7dB & SNR=10dB)

On the basis of the simulation results obtained after running the MATLAB code, following are the results which were concluded.

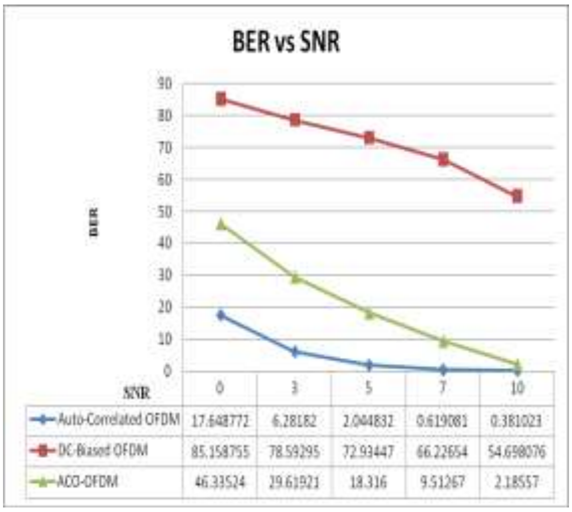


**Figure 4.4: BER vs. SNR**

From Figure 4.4, it is very clear that the proposed methodology of Auto-correlated optical OFDM in comparison to the earlier existing signalling techniques such as DC-biased OFDM and ACO-OFDM the BER of Auto-correlated optical OFDM is very less and hence the image quality is optimum.

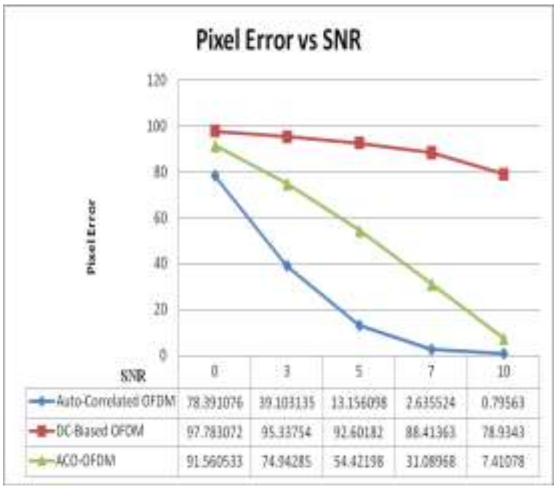


**Figure 4.5: Pixel Error vs. SNR**

The only flaw in the proposed methodology is that the total runtime of the process is high. The transmitting time of the input image and the receiving time of the same image is higher as compared to that of DC-Biased OFDM and ACO-OFDM this is because of the reason that in Auto-correlated optical OFDM the negative and the non-negative part of the signal is being processed whereas in DC-Biased OFDM and ACO-OFDM the negative part is either eliminated or being suppressed to zero

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