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Afrah Ali
University of Wollongong in Dubai

Nidhal Abdulaziz
University of Wollongong in Dubai, nidhal@uow.edu.au

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Dimming Control in Visible Light Communication using RPO-OFDM and Concatenated RS-CC

Afrah Ali Nidhal Abdulaziz
Faculty of Engineering and Information Science, University of Wollongong in Dubai
United Arab Emirates
afrahali.k@hotmail.co.uk, nidhalabdulaziz@uowdubai.ac.ae

Abstract: *Increasing wireless data traffic is creating pressure on the conventional dwindling radio frequency spectrum. A new and reliable communication medium becomes a necessity. Visible Light Communication (VLC), a subset of optical wireless communication uses the visible light spectrum between 400 and 800 THz as a medium for communication. VLC utilizes the illumination of LED to establish a communication medium. The research focused on achieving a successful VLC communication link at low intensities of light without affecting the speed, accuracy and efficiency of VLC. The achievement of the paper was to devise a method to reduce the LED brightness, reducing energy consumption and most importantly maintain a reliable, efficient and successful VLC communication link at low intensities of LED. The research comprises of a Reverse Polarity Optical-Orthogonal Frequency Division Multiplexing (RPO-OFDM) modulator, a Forward Error Correction (FEC) encoder block that uses concatenated Reed Solomon – Convolutional Coding, a digital PWM dimming control circuit, an RPO-OFDM demodulator and a FEC decoder. The decoding is performed using the Berlekamp–Massey algorithm and the Viterbi algorithm. Extensive research on various modulation schemes, coding and error correction techniques along with various driver circuit design for dimming control in VLC were thoroughly investigated to conclude the best reliable solution for dimming control in VLC.*

Keywords: *RPO-OFDM, VLC, BER, SNR, RS-CC, PWM, DCO-OFDM, ACO-OFDM, IM/DD.*

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1. Introduction

Optical data communication should be reliable even at low intensities of light. Power consumption and lighting quality are one of the crucial aspects in VLC systems. A reliable and effective dimming control technique needs to be developed in order to control the brightness of the light without hampering the communication medium. The main aim of introducing dimming control to VLC is to minimize the power consumption of the LEDs and for user convenience. The LED is used as the source of light and as a medium for wireless communication. Hence, it is not desirable to switch the LED on with a 100% brightness at all the time. An illumination between the range 200-1000 lux is required for a typical office environment [1]. Hence, the illumination should be maintained between these ranges. Dimming control has an adverse effect in VLC systems. Establishing a communication medium after dimming the LED light results in reducing the average signal strength. It also accounts to increase the Bit Error Rate (BER) and Signal to Noise Ratio (SNR) while reducing the data rate. Hence, proposing and developing a suitable solution for dimming control in VLC was indeed a challenge and a most recent research topic.

The LED driving signal in optical communication must be real and positive [2], [3]. Hence, the proposed digital Pulse Width Modulation (PWM) dimming control solution uses Optical-Orthogonal Frequency Division Multiplexing (O-OFDM) which uses real and positive signals for VLC optical communication. The real and positive signal is obtained by constraining the input to the Inverse Fast Fourier Transform (IFFT) of OFDM to have a Hermitian Symmetry. Reverse Polarity Optical-OFDM (RPO-OFDM), a type of O-OFDM was used in the research to modulate data onto the light intensity. The RPO-OFDM was superimposed on the relatively slow PWM dimming signal which acts as the carrier. The RPO-OFDM is capable of utilizing the entire PWM pulse by reversing the polarity at its off states thereby ensuring data transmission at all

time. The PWM duty cycle is varied depending on the required dimming percentage. The PWM pulse acts both as the dimming and carrier signal. Improved results in terms of BER (in terms of SNR) was obtained by adding FEC codes such as the concatenated Reed Solomon-Convolutional Coding (RS-CC). Several testing and comparisons were performed in terms of BER (in terms of its relative SNR) to conclude the lowest intensity of light required to successfully communicate using VLC technology.

2. Literature Review

Visible Light Communications (VLC) uses the visible light spectrum as a medium for wireless communication. VLC uses the fast switching LEDs as the light source to provide illumination and communication. The key prospect of VLC is to achieve indoor wireless short range communication at high data rate with low BER and SNR effectively and efficiently. Therefore, at low intensities of light, the performance of the VLC link will be hampered. A reliable communication link should be possible even at low intensities of light. This section describes the history of dimming control techniques to ensure a reliable and successful communication at low intensities of light. The main aim of the dimming control is to ensure that the data remains consistent even when the end user dims the light source arbitrarily.

Analog dimming technique was the first technique used for dimming control in VLC. Analog dimming used Continuous Current Reduction (CCR) technique to control the LED illumination. In CCR, the current flow through an LED was directly reduced by reducing the LED voltage to achieve dimming [2], [4]. However, this caused the LED's to be under driven and resulted in chromaticity shifts [2]. Chromaticity can be defined as an objective specification that determines the colour quality of the LED regardless of it luminance. Hence, the analog dimming was later replaced by the digital PWM dimming which varied the duty cycle to cause LED dimming.

The data to be transmitted was modulated using modulation techniques and then was superimposed on the dimming PWM signal (carrier signal). Hence, reducing the PWM duty cycle reduced the average signal strength and was subjected to external disturbances such as noise. Simple digital modulation schemes such as Pulse Width Modulation (PWM), Pulse Position Modulation (PPM) and Pulse Amplitude Modulation (PAM) were initially used in the dimming control of VLC [1], [2], [4]–[10].

Later a combination of these schemes were used to achieve the desired dimming performance in terms of less Bit Error Rate (BER), low Signal to Noise Ratio (SNR) and high data rates. The Optical-Orthogonal Frequency Division Multiplexing (O-OFDM) dimming schemes were introduced in 2011 [11]. Simple OFDM based schemes such as the bipolar Direct Current-biased Optical-OFDM (DCO-OFDM) and Asymmetrically Clipped Optical – OFDM (ACO-OFDM) schemes were commonly used to achieve dimming yet maintaining reliable communication links [6], [12]–[15]. In all the modulation methods mentioned above, data cannot be modulated on to the PWM carrier signal at off pulses (when the PWM pulse is zero). Hence, a continuous transmission is not achieved. Moreover, when PWM dimming is introduced, more errors occur besides the drawback of having non continuous transmission. This resulted in unreliable VLC communication links using dimming control. Later, in 2015, the most recent approach based on OFDM scheme known as the Reverse Polarity Optical-OFDM (RPO-OFDM) was introduced. The RPO-OFDM was capable of utilizing the full LED dynamic range by reversing the polarity of the PWM pulses thereby ensuring full transmission at all times. It proved to provide better results than other O-OFDM schemes in terms of BER, SNR and data rates [1], [2], [6], [15].

3. System Design

This section provides a detailed description of the system design block diagram and its simulation on Matlab. The research achieved the digital PWM dimming technique to control the dimming in Visible Light Communication (VLC) using RPO-OFDM. The O-OFDM symbols to be transmitted are mapped into constellations by a QAM modulator. The data is incorporated into the light using (Reverse Polarity Optical-Orthogonal Frequency Division Multiplexing) RPO-OFDM modulation technique. Further sections explain the simulation procedure and results obtained in detail.

3.1 Dimming Control Circuit in VLC

The proposed transmitter block diagram for achieving dimming control in VLC is shown in Figure 1. Detailed explanation of each block is provided in the following sections. The Forward Error Correction (FEC) block shown in Figure 1 is the concatenated Reed Solomon-Convolutional Coding (RS-CC) block. RS and CC are the types of FEC codes.

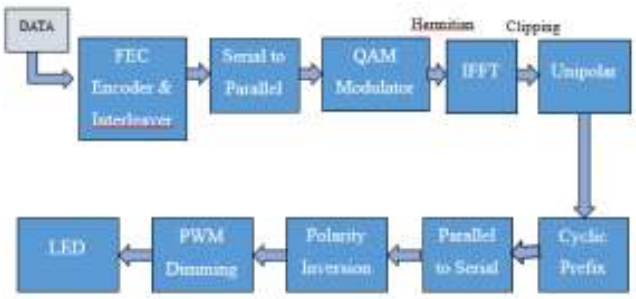

Figure 1 Transmitter Block Diagram for Dimming Control in VLC using RPO-OFDM and FEC

The receiver for dimming control in VLC using RPO-OFDM and concatenated RS-CC consists of the transmitter counter parts in the reverse order of

operations as shown in Figure 2. Detailed explanation of each block is provided in the following sections.

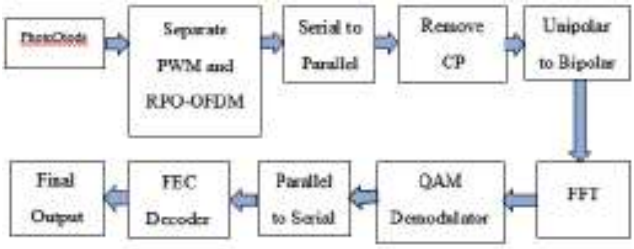

Figure 2 Receiver Block Diagram for Dimming Control in VLC using RPO-OFDM and FEC

3.1.1 Data Generation

A random data generator is the first block in the dimming control transmitter. A random data generator ensures the avoidance of long sequences of 0s and 1s which might cause problem in recovering the time at the receiver end. The data generated for the simulation used a probability of 50% to generate 1s and 0s. The data generated are converted from parallel to serial before passing it through the FEC encoder block.

3.1.2 FEC Encoder/Decoder

The random data generated at the transmitter was encoded by introducing redundancy using the Forward Error Correction (FEC) encoder block consisting of concatenated Reed Solomon and Convolutional Coding (RS-CC). Spreading redundant bits over the channel bandwidth resulted in providing a better result in terms of BER for a given SNR. FEC methods such as the Reed Solomon (RS) and the Convolutional Coding (CC) have different characteristics towards BER and hence a combination of these two should provide incredible performance results. RS codes are not effected by burst errors and CC is not susceptible to random noise as much as RS [34], [35]. Hence, RS and CC was concatenated to achieve the desired performance level.

The RS-CC decoding was performed in reverse order of operations at the receiver side as shown in Figure 9. The RS decoding was performed using the Berlekamp-Massey decoding algorithm and the CC decoding was performed using the Viterbi decoding algorithm in the receiver. The Viterbi algorithm uses a trellis diagram to estimate the actual bit sequence excluding the bit errors [27]. The Berlekamp–Massey algorithm functions by finding the shortest Linear Feedback Shift Register (LFSR) for the received data sequence [27]. The decoding algorithms can be used in two forms such as the hard decision or soft decision. The difference lies in what form the bits are received in the receiver. The soft decision decoding uses the multi bit quantization (three or four bits for precision) on the received channel whereas the hard decision decoding use 1 bit quantization on the received channel [27], [28]. In this research, hard decision was used for FEC decoding.

3.1.3 Interleaver/De-Interleaver

Interleaving is performed to prevent the occurrence of long consecutive errors. Long consecutive errors effect several bits in a row and result in burst losses. The encoded RS-CC data are interleaved using the block size of the RS-CC coded bits per symbol. A two-step permutation defines the interleaver. First permutation maps the coded RS-CC bits to the nonadjacent OFDM subcarriers [34]–[36]. This is to avoid fading effects to the neighboring bits when one bit is affected by deep fade effects and hence ensures the correction of fading.

3.1.4 OFDM Modulator/Demodulator

The output from the interleaver block was fed to the OFDM modulator block. OFDM is a multicarrier wideband modulation technique which is capable of transmission over dispersive channels and solves the problems associated with multipath reception. The subcarriers in OFDM are orthogonal and independent to each other. Signals are orthogonal if the integral of their product equals zero. The subcarriers were separated from each other using guard intervals.

The signal obtained from the interleaver block was then split into several other signals over the same frequency range. Each signal was modulated separately and a demultiplexer at the receiver side combined all the signal together to obtain the original signal. An OFDM transmitter block consists of the following blocks as shown in Figure 3.

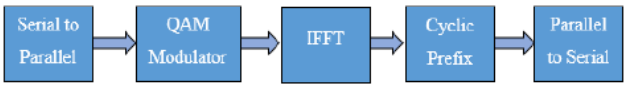

Figure 3 OFDM Transmitter Block Diagram

The interleaved data received from the interleaver was converted from serial to parallel using the serial to parallel converter block. The parallel data obtained after the conversion was modulated using QAM. The research used QAM for mapping the data symbols into constellations. The QAM signal consisted of two carriers, I signal (cosine signal) and the Q signal (sinusoidal signal) with different phase and the same frequency. However, both I and Q signals were combined at the transmitter and at the counterpart QAM demodulator, the carriers were separated to extract the data. The QAM modulated symbols were then converted from the frequency domain to time domain samples using Inverse Fast Fourier (IFFT) transform. IFFT generates waveform with orthogonal frequency components and hence is useful in the application of OFDM. The time domain signal was converted back to the frequency domain using an FFT as a function of sampling period and the number of samples used at the receiver end in reverse order of operations.

The multipath delay caused the signal to be distorted by the echo of other signals. A cyclic prefix (CP) block was inserted after the IFFT block to avoid Inter Symbol Interferences (ISI) at the transmitter. Figure 13 shows the insertion of Cyclic Prefix in OFDM. When the CP was more than the multipath delay, ISI was be completely resolved. CP was performed by concatenating the end portion of the OFDM symbol to its beginning as shown in Figure 13. At the receiver, the CP was removed in the reverse order of operations as shown in Figure 9. The final step in an OFDM transmitter was to convert all the parallel data back to serial data before adding AWGN. This was performed by passing the output of the CP block to a parallel to serial converter. At the receiver end, the reverse order of operations were performed. It was observed that the data rate conveyed by each subcarrier was reduced when the number of parallel transmissions were increased. This in turn lengthened the symbol period. Hence, it was observed that the reflected wave delay time was suppressed to 1 symbol time. Figure 4 shows the OFDM demodulator block diagram.

Figure 4 OFDM Receiver Block Diagram

3.1.5 Optical-OFDM (O-OFDM)

It is extremely important to use an O-OFDM block for the research simulation instead of the conventional OFDM block to achieve better results in terms of BER, SNR and data rates. O-OFDM deals with the modulation of optical data. Since VLC uses visible light (optical communications) as a medium for communication, the OFDM signal used for the research simulation was an O-OFDM signal. O-OFDM requires that the LED driving signal should be real and positive. Real and positive signals were obtained when the signal was constrained to have a Hermitian symmetry. Hermitian symmetry takes all the real part of the signal. Hence, O-OFDM signal was achieved by constraining the input to the IFFT to have Hermitian symmetry [1]. The block diagram of an O-OFDM transmitter is shown below in Figure 5. The demodulation was performed at the O-OFDM counterpart in reverse order of operations.

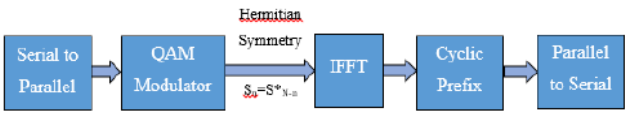

Figure 5 O-OFDM Transmitter Block Diagram

A matrix B = (bij) is defined to be Hermitian matrix if B = BH where BH represents the conjugate transpose of B. The following was the Matlab instruction used in the simulation to convert the output from the QAM modulator to hermitian symmetry before passing it through the IFFT block where X was the output signal from the QAM modulator block.

The digital dimming control was achieved by modulating the data using Reverse Polarity Optical – Orthogonal Frequency Division Multiplexing (RPO-OFDM) and incorporating it with PWM dimming carrier pulse. Figure 6 shows the block diagram of a RPO-OFDM transmitter Block.

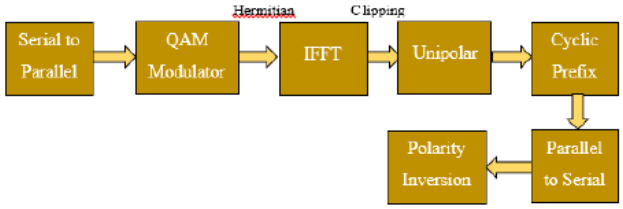

Figure 6 RPO-OFDM Block Diagram

Figure 7 shows the conversion of O-OFDM to RPO-OFDM. ACO-OFDM was obtained after clipping all the negative values of the O-OFDM signal at zero before CP insertion.

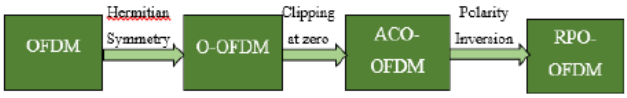

Figure 7 Conversion of OFDM to RPO-OFDM Block Diagram

The OFDM signal was converted into O-OFDM symbols by constraining the input to the IFFT to have a Hermitian symmetry. The O-OFDM signal was clipped at zero, keeping all positive values to obtain the ACO-OFDM bipolar signal. The RPO-OFDM signal was obtained by superimposing the ACO-OFDM signal on the PWM pulse by reversing the polarity of the PWM pulse at zero positions. Figure 8 shows the ACO-OFDM signal obtained after clipping off all the negative values at zero.

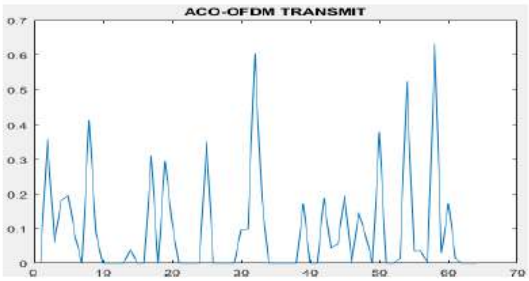

Figure 8 ACO-OFDM Clipped Signal

The ACO-OFDM signal so obtained was then incorporated onto the PWM dimming carrier signal by reversing the polarity at the off pulses of PWM to achieve RPO-OFDM transmission. This was achieved by adding and subtracting the *iofdm (t)* with the *ipwm (t)* using the following equation [1]. T represents the pulse width of the PWM dimming signal and *Tpwm* represents the period.

$$i_{LED}(t) = \begin{cases} \text{ipwm (t)} - \text{m x iOFDM (t)}, & 0 \le t \le T \\ \text{ipwm (t)} + \text{m x iOFDM (t)}, & T \le t \le Tpwm \end{cases}$$

where,

$$\text{iOFDM (t)} = \sum_{n=0}^{N-1} \text{Sn exp(j}\omega\text{nt)} \ , 0 \le t < TOFDM$$

and,

$$i_{PWM}(t) = \begin{cases} I_H, & 0 \le t < T \\ I_L, & T < t \le Tpwm \end{cases}$$

I_H is the 'on' level of the pulse and I_L is the off level of the PWM pulse [1]. The on and off pulses of the PWM pulse is regarded as the PWM driving currents. These results and conclusions are in perfect agreement with the results obtained in [1]. Figure 9 shows the RPO-OFDM signal superimposed over a PWM duty cycle of 50% (ACO-OFDM superimposed on PWM dimming signal) at the transmitter after the application of equation 9. It can be noted from Figure 9 that the modulating signal above 1A (IH) is clipped to ensure that 1A is the maximum PWM current that drives the LED.

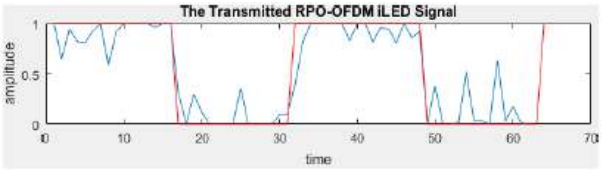

Figure 9 The superimposition of RPO-OFDM with PWM pulse with a duty cycle of 50%

The PWM pulse train drives the LED at constant current level and hence any change in the variation of the PWM duty cycle changed the current that flowed through the LED considerably. The period of the PWM was kept constant and the duty cycle was varied according to the required dimming target. The PWM duty cycle was varied using the following equation [1],

$$D = T/Tpwm$$

where D is the duty cycle, T is the pulse width and Tpwm is the period. Figure 19 shows the PWM dimming performed on a RPO-OFDM modulated data using 50% PWM duty cycle. The modulated RPO-OFDM data was superimposed onto the PWM with a 50% duty cycle. A PWM with a 100% duty cycle lights up the LED at its maximum brightness [4], [7], [12], [37]. Reducing the PWM duty cycle reduced the intensity of light. This in turn resulted in reduced average signal strength and more BER. However, with the help of FEC, the BER was reduced to some extent. Figure 30 shows the BER Vs SNR graph for PWM dimming at a duty cycle of 50%. The output from the dimming block is converted from parallel to serial before subjecting it to AWGN.

3.1.7 Additive White Gaussian Noise (AWGN)

The output signal from the transmitter was subjected to AWGN which was removed at the receiver. Figure 10 shows the insertion of AWGN between the transmitter and receiver. AWGN was added to intrinsic noise in the model. Across the frequency band, AWGN poses uniform power with a normal distribution in the time domain.

Figure 10 AWGN block insertion

Figure 11 shows the received signal with noise for a RPO-OFDM signal dimmed with a 50% duty cycle. At the receiver, the counterparts of the transmitter perform in the reverse order of operations to obtain the original data.

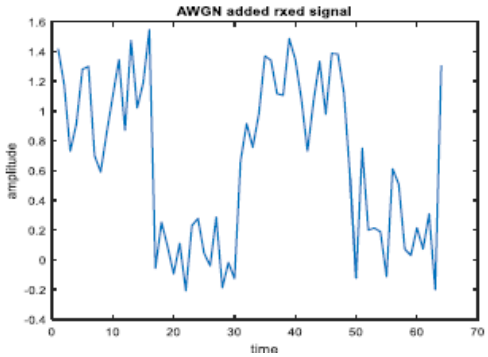

Figure 11 AWGN added RPO-OFDM signal superimposed on a PWM dimming

4. Simulation Results

This section discusses the simulation results obtained for the dimming control circuit using RPO-OFDM with and without FEC codes such the Reed Solomon and Convolutional Coding. The simulation was performed on MATLAB.

4.1 Relationship of PWM Dimming on LED Brightness

This section describes the results obtained after implementing the algorithm discussed in Chapter 3. Figure 12 shows the relationship obtained between the perceived LED brightness and the PWM dimming after simulating on Matlab. The LED brightness can be varied when the PWM duty cycle is adjusted. The following equation was used to explain the effect of PWM duty cycle on the perceived LED brightness.

$$\text{Perceived LED brightness} = 100 * \sqrt{\frac{\text{PWM duty cycle (simulated) (\%)}}{100}}$$

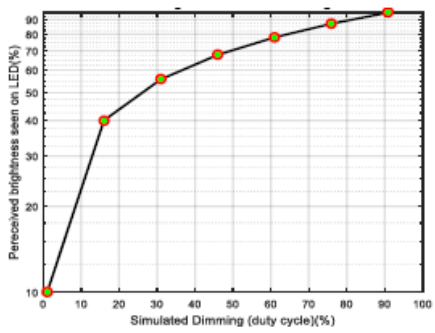

Figure 12 Perceived brightness on LED vs. simulated dimming

It can be observed from the above figure that when the duty cycle is reduced to 50% in the simulation of PWM dimming, the LED appears to have 70% brightness. The simulated results obtained for perceived LED brightness vs. simulated dimming is in perfect agreement with the simulated results of [1]. The main aspect of the research is to propose the minimum LED brightness required to establish a successful and reliable VLC communication link with reduced BER. Section 4.2 simulates various dimming ranges and proposes the minimum LED brightness required to communicate using VLC successfully.

4.2 Simulation Results for Various Dimming Ranges With and Without FEC

This section describes the simulation results obtained for various PWM dimming ranges in terms of BER a certain SNR. The main aim of the research research is not only to establish a successful VLC communication link with minimum LED brightness, but also to reduce the BER significantly along with reduced power consumption. The PWM duty cycle was varied to achieve different dimming ranges where 100% was considered to be the highest LED brightness level. It is assumed that 1 ACO-OFDM (since it's clipped) symbol is sent in every 1s. Keeping this assumption, the RPO-OFDM and PWM superimposition is performed over 64s of a PWM pulse. The superimposition of the ACO-OFDM over the PWM (100% duty cycle) by reversing the PWM polarity results in the formation of RPO-OFDM symbols

4.2.1 Simulation results for PWM dimming using 100% duty cycle

This section describes the simulation results obtained for a PWM duty cycle of 100%. RPO-OFDM symbol formation obtained after the superimposition of the ACO-OFDM over the PWM (100% duty cycle) by reversing the PWM polarity is shown in Figure 13. Figure 14 shows the BER vs. SNR graph obtained for 100% duty cycle without concatenated RS-CC.

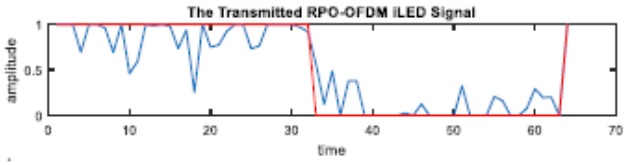

Figure 13 RPO-OFDM signal superimposed on 100% duty cycled PWM pulse

As mentioned in section 3, the amplitude of the superimposed RPO-OFDM and PWM signal is considered to be the average LED driving current. The RPO-OFDM is clipped at 1A. The LED is considered to be fully bright at a 100% PWM duty cycle and hence there shouldn't be any problem in establishing a reliable and successful VLC communication link. The BER vs. SNR graph without FEC obtained for 100% duty cycle shown in Figure 14 proves the statement. It can be noted that a BER of 10^{-3} is obtained at a SNR of 13 dB and a BER of 10-4 is obtained at 15 dB. The acceptable BER to establish a successful VLC communication link is considered to be 10^{-2}, 10^{-3} or lower [1], [9], [29], [30], [38].

It is noticed that good BER of 10^{-4} is obtained without any error correction. Figure 15 shows that both the input data at the transmitter and the final output data at the receiver are highly similar. Hence, it can be concluded that at 100% PWM duty cycle, the LED brightness is 100% and the best VLC communication occurs at this level in terms of BER of 10^{-3} at 15dB SNR.

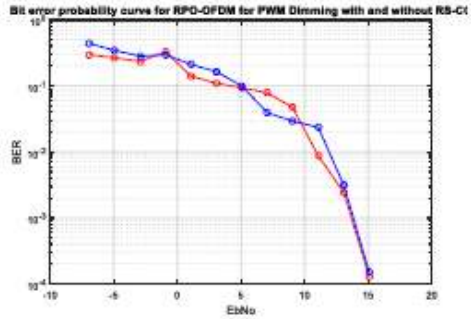

Figure 14 BER vs. SNR RPO-OFDM graph with PWM duty cycle of 100% with and without concatenated RS-CC

Figure 15 Original Input Message and the Final Received Output

4.2.2 Simulation results for PWM dimming using 75% duty cycle

The PWM duty cycle was reduced to 75% to test the effect of dimming control in VLC in terms of BER vs. SNR. The RPO-OFDM data was superimposed on to the PWM pulse with a duty cycle of 75% as shown in Figure 16. The SNR required to achieve a BER of 10^{-3} for a RPO-OFDM modulated data with 75% duty cycle decrease was slightly higher compared to the 100% PWM pulse as shown in Figure 17 by a difference of 2.6dB.

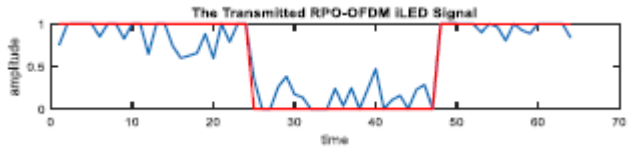

Figure 16 The RPO-OFDM signal at the transmitter and receiver for 75% PWM duty cycle

A BER of 10^{-3} was obtained at 15.6dB without Convolutional Coding (CC) encoding. However, when CC was included, BER of 10^{-3} was obtained at SNR 15. 10^{-3} is an acceptable BER for dimming in VLC. A slight improvement in the SNR rate was noticed. Hence, the power was slightly reduced by 0.6dB with the introduction of CC to the dimming at 75% duty cycle.

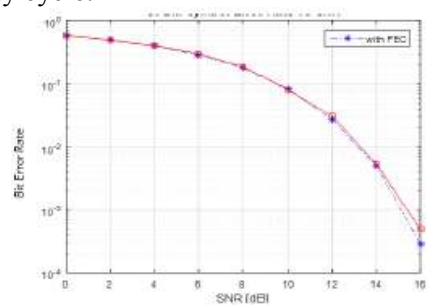

Figure 17 BER vs. SNR graph for a RPO-OFDM data with PWM dimming using a duty cycle of 75% with and without FEC

4.2.3 Simulation Results for PWM Dimming using 50% Duty Cycle

The PWM duty cycle was reduced to 50% to test the effect of dimming control in VLC in terms of BER vs. SNR. The RPO-OFDM data was superimposed on to the PWM pulse with a duty cycle of 50% as shown in Figure 18. The BER of a RPO-OFDM modulated data with 50% duty cycle decrease was higher compared to the 75% PWM pulse by $10^{-0.8}$ as shown in Figure 31.

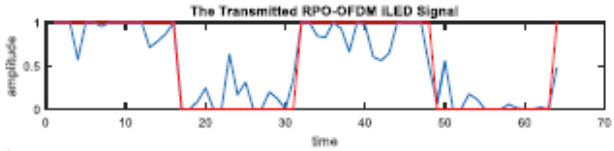

Figure 18 The RPO-OFDM signal at the transmitter and receiver for 50% PWM duty cycle

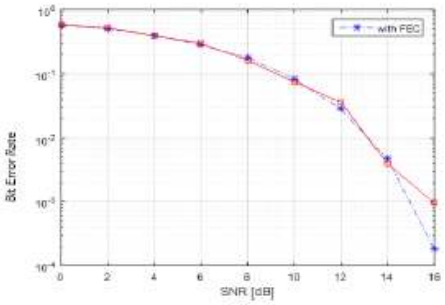

Figure 19 BER vs. SNR graph for PWM duty cycle of 50% for an RPO-OFDM

A BER of 10^{-3} is obtained at 16dB without Convolutional Coding (CC) encoding. However, when CC was included, BER of 10^{-3} was obtained at SNR 15. 10^{-3} is an acceptable BER for dimming in VLC. A slight improvement in the SNR rate was noticed. Hence, the power was slightly reduced with the introduction of CC to the dimming at 50% duty cycle.

4.2.4 Simulation Results for PWM Dimming using 35% Duty Cycle

The PWM duty cycle was reduced to 35% to test the effect of dimming control in VLC in terms of BER vs. SNR. The RPO-OFDM data was superimposed on to the PWM pulse with a duty cycle of 35% as shown in Figure 20. The SNR required to achieve a BER of 10^{-3} for a RPO-OFDM modulated data with 35% duty cycle was much higher compared to the SNR required for the 50% PWM pulse by a difference of 14dB as shown in Figure 21.

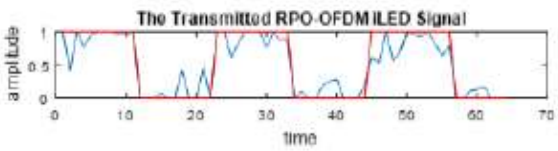

Figure 20 The RPO-OFDM signal superimposed on the PWM pulse with 35% duty cycle

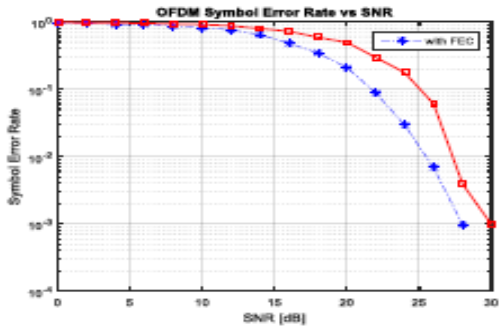

Figure 21 BER vs. SNR for an RPO-OFDM data with PWM dimming control using

A BER of 10^{-3} is obtained at SNR of 30 is obtained without Convolutional Coding (CC) encoding. However, when CC was included, BER of 10^{-3} was obtained at SNR 28. Though 10^{-3} is an acceptable BER for dimming in VLC, the SNR value is higher compared to other duty cycles below 35%. A good improvement in the SNR rate was noticed. Hence, the power was slightly reduced with the introduction of CC to the dimming at 35% duty cycle.

4.2.5 Simulation Results for PWM Dimming Using 25% Duty Cycle

The duty cycle was reduced to 25% to test the effect of dimming control in VLC in terms of BER vs. SNR. The RPO-OFDM data was superimposed on to the PWM pulse with a duty cycle of 25% as shown in Figure 22. The BER vs. SNR plotted for a RPO-OFDM modulated data with 25% duty cycle decrease is shown in Figure 23.

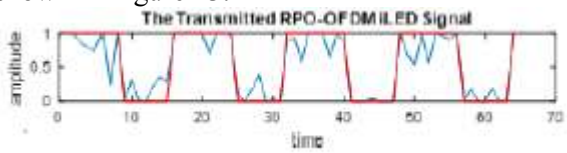

Figure 22 The RPO-OFDM signal superimposed on the PWM pulse with 25% duty cycle

A BER of $10^{-2.6}$ was obtained at SNR of 30dB without Convolutional Coding (CC) encoding. However, when CC was included, BER of $10^{-2.8}$ was achieved at SNR 26. A good improvement in the SNR rate was noticed. Hence, the power was slightly reduced by 4dB with the introduction of CC to the dimming at 25% duty cycle.

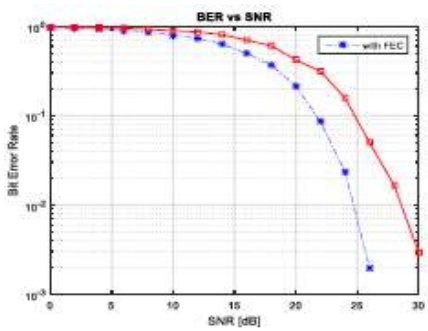

Figure 23 BER vs. SNR graph for a RPO-OFDM data with PWM dimming using a duty cycle of 25% with and without FEC

4.2.6 Simulation Results for PWM Dimming Using 20% Duty Cycle

The duty cycle was reduced to 20% to test the effect of dimming control in VLC in terms of BER vs. SNR. The RPO-OFDM data was superimposed on to the PWM pulse with a duty cycle of 20% as shown in Figure 24. As it can be observed from the BER vs. SNR graph for 20% duty cycle shown in Figure 25, there was no observable difference between the BER vs. SNR with FEC for 25% and 20% duty cycle. However there is a slight variation in the BER without FEC.

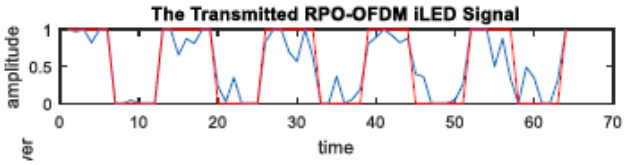

Figure 24 The RPO-OFDM signal superimposed on the PWM pulse with 20% duty

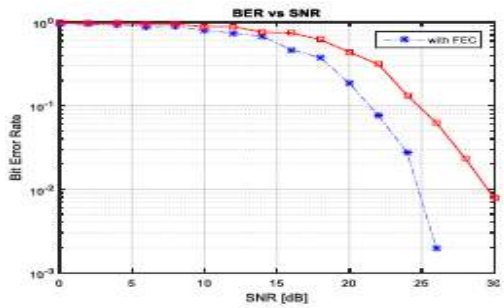

Figure 25 BER vs. SNR graph for a RPO-OFDM data with PWM dimming using a duty cycle of 20% with and without FEC

A BER of $10^{-2.1}$ was obtained at 30dB without Convolutional Coding (CC). However, when CC was included, BER of $10^{-2.8}$ was obtained at SNR 26dB. A good improvement in the SNR rate by 4dB was noticed after the inclusion of convolutional coding. Hence, the power was slightly reduced with the introduction of CC to the dimming at 20% duty cycle. However, this result could have been further improved with concatenation of CC with RS.

4.2.7 Simulation Results for PWM Dimming using 10% - 15% Duty Cycle

The PWM duty cycle was reduced further up to 10% - 15% to test the effect of dimming control in VLC in terms of BER vs. SNR. The RPO-OFDM data was superimposed on to the PWM pulse with a duty cycle of 10 and 15% as shown in Figure 26 and Figure 27. The BER and SNR of an RPO-OFDM modulated data with 10% and 15% duty cycles shown in Figure 28 and Figure 29 shows a high BER unsuitable for VLC communication with dimming control.

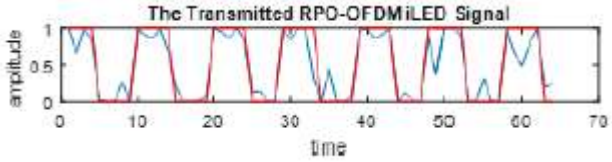

Figure 26 The RPO-OFDM signal superimposed on the PWM pulse with 15% duty cycle

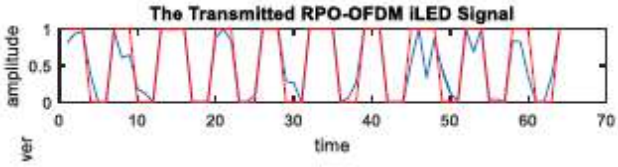

Figure 27 The RPO-OFDM signal superimposed on the PWM pulse with 10% duty cycle

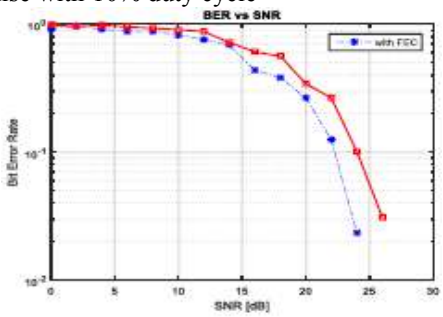

Figure 28 BER vs. SNR graph for a RPO-OFDM data with PWM dimming using a duty cycle of 15% with and without FEC

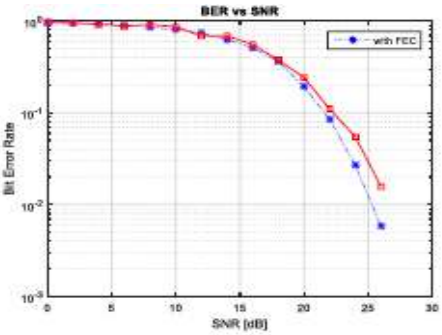

Figure 29 BER vs. SNR graph for a RPO-OFDM data with PWM dimming using a duty cycle of 10% with and without FEC

A BER of $10^{-1.7}$ was obtained at SNR of 26 is obtained without CC for 15% duty cycle. However, when CC was included, BER of $10^{-1.8}$ was achieved at SNR 24dB. A BER of $10^{-1.8}$ was obtained at SNR of 26.1dB is obtained without CC for 10% duty cycle. BER of $10^{-2.4}$ was achieved at SNR 26dB. A good improvement of 3.1dB in the SNR rate was noticed. Hence, the power was slightly reduced with the introduction of CC to the dimming at 15% duty cycle. However, the BERs obtained even after adding CC was high. A reliable establishment of VLC communication link cannot be guaranteed with such a high BER.

Figure 30 and Figure 31 shows that the original data sent and the received data are noticeably different. This could be because, when the PWM duty cycle is reduced to 10% and 15%, as per the information obtained from Figure 12, the LED perceived LED brightness is only 30%. The signal strength was tremendously weaken and was easily affected by noise thereby increasing the BER.

Figure 30 Original message and final message obtained for PWM duty cycle of 15%

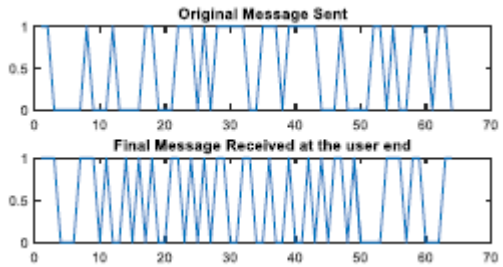

Figure 31 Original message and final message obtained for PWM duty cycle of 10%

It was noticed that PWM duty cycle below 20% resulted in high bit error rates which was unsuitable to achieve reliable, efficient and accurate communication using VLC. Hence, no further simulation for PWM duty cycle below 10 was performed. Table 1 briefs up the simulation results obtained.

Table 1 Simulation Results for PWM dimming control in VLC using RPO-OFDM

PWM Duty Cycle (%)	Perceived LED Brightness (%)	Without FEC		With FEC	
		SNR	BER	SNR	BER
100	100	15	10^{-4}	No change	No change
		13	10^{-2}	No change	No change
75	86.6	15.6	10^{-5}	15	10^{-5}
50	70.7	16	10^{-5}	16	$10^{-3.8}$
35	59.1	30	10^{-5}	28	10^{-5}
25	50	30	$10^{-2.8}$	26	$10^{-2.8}$
20	44.7	30	$10^{-2.1}$	26	$10^{-2.8}$
15	38.7	26	$10^{-2.7}$	24	$10^{-2.8}$
10	31.6	26.1	$10^{-2.8}$	26	$10^{-2.4}$

5. Conclusion and Future Work

High speed data communication can be achieved using Visible Light Communication with improved energy efficiency and security. Dimming control in VLC ensures that communication is possible even at low intensities of light. The significance of a LED dimming control system in a VLC link is that it reduces the energy consumption, allows adjustment of LED brightness as per user convenience by guaranteeing that the VLC communication link is not hampered. The research simulated a PWM dimming control circuit that uses RPO-OFDM to incorporate the data into the light intensity. The PWM dimming is achieved by varying the duty cycle of the PWM pulse to an extent such that reliable communication is maintained with a low BER at a relatively lower SNR. RPO-OFDM is indeed a latest approach to dimming control in VLC. The research also conducted extensive literature review on various modulation based dimming schemes, coding schemes, circuit designs, performance improvement methods and adaptive techniques for dimming control in VLC.

The simulation results obtained for the research conveys that up to a duty cycle of 50%, the BER is only 10^{-3} at considerably low SNR rates. The FEC did not show remarkable effect on duty cycles between 50% - 100%. When the duty cycle was further decreased up to 20%, the BER increased. The BER was significantly reduced using CC for duty cycles between 20% - 50% by 10^{-1} at improved SNR by 2dB-6dB. Below 20% duty cycle, the BER obtained was high and will not guarantee a successful VLC communication. A PWM duty cycle of 20% with a BER of $10^{-2.8}$ (close to 10^{-3}) obtained after the inclusion of CC could be concluded as the minimum PWM duty cycle required to establish a successful VLC communication. A PWM duty cycle with RPO-OFDM modulated data having BER of 10^{-3} at SNR 15-20 dB is considered to be suitable for reliable VLC communication according to [1], [9], [12]. Up to 35% PWM duty cycle, BER of 10^{-3} can be achieved with FEC at an SNR of 28 dB. However, with a lower SNR rate of 26dB, a BER of $10^{-2.8}$ is achieved. Though the BER for 20% is slightly higher than the BER of 35%, the SNR is relatively lower compared to that of 35%. Similarly, with 20% PWM duty cycle, the perceived LED brightness is approximately 45% whereas with 35% duty cycle, the perceived dimming is only 60%.

The BER vs. SNR results achieved with FEC are quite similar to the results obtained in [34]. However, [34] uses soft decoding decision (hard decision used in the research) and is not used along with PWM dimming or RPO-OFDM. In that context, it can be claimed that the results obtained in the research is acceptable even after introducing a dimming circuit. The BER of 10^{-3} or lower is achieved at very low SNR rates such as 5dB and 10dB in [36]. However, in this research, the SNR required to achieve a BER of 10^{-3} was obtained to be within a range of 15dB-28dB with FEC. This huge differences in the SNR can be justified since the research uses PWM dimming signal as the carrier for the RPO-OFDM modulating signal. Introducing dimming reduces the signal strength resulting in increased BER due to high noise interferences.

Hence, it can be concluded that the lowest PWM duty cycle required to establish a successful VLC communication is 45%. Dimming the LED by reducing the PWM duty cycle by 20% would result in 45% LED brightness as per Figure 12. Hence, the LED is dimmed to less than half of its original brightness using digital PWM dimming using RPO-OFDM and concatenated RS-CC.

The BER was improved using FEC codes such as the concatenated RS-CC. However, the RS code was used to improve the BER only for the 100% duty cycle. Future research can significantly improve the BER obtained for various dimming ranges by concatenating the RS along with CC. By doing so, the minimum LED brightness required to communicate using VLC could be achieved lower than 45%. Various CC rates and RS rates could be tested to achieve a lower BER in the future. Future research could also focus on finding the effect of using different communication channels such as Reyleigh, Multipath etc… on dimming control in VLC. Practical hardware implementation of the dimming circuit can also be a future work.

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Afrah Ali is a Telecommunications Engineer graduated from the University of Wollongong in 2016. She has been working on the research development of dimming control in Visible Light Communication from September 2015 as part of her thesis. She has also contributed to several other university projects. She has conducted extensive research development of autonomous indoor quad copter navigation in GPS denied environment. She has several publications on various other research topics. She is a member at the IEEE and Engineers Australia.

Nidhal Abdulaziz is currently working as Associate Professor at the Faculty of Engineering and Information Sciences, University of Wollongong in Dubai. Before that she was the Director for Electronics and Electrical Engineering, Heriot Watt University (HWU) Dubai Campus, she has received her PhD from Monash University, Australia, in Electrical and Computer Systems Engineering.