Li-Fi concept in terms of modulation techniques

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***Abstract* -** Li-Fi (light fidelity) is a bidirectional wireless system that transmits data via LED or infrared light. Li-Fi technology only needs a light source with a chip to transmit an internet signal through light waves. The system has a receiver to pick up light signals and transmitter to send light signals back to the lamp using infrared light. The technology has high data rate as well as high spectral efficiency and also robust against inter symbol interference. Different forms of OFDM (a multicarrier modulation technique) are being used for Li-fi scheme. This paper reflects the theoretical study of various modulation techniques of Li-fi technology.

Keywords— light fidelity; orthogonal frequency division multiplexing; machine learning; dimming;

I. Introduction

With the escalating need for wireless data communication, the radio spectrum below 10 GHz has proven inadequate to meet the demand. As a result, the wireless communication industry has started exploring the use of radio spectrum frequencies above 10 GHz to address this challenge. Li-Fi, also known as Light-Fidelity, represents a development in this trend towards utilizing higher frequencies within the electromagnetic spectrum [1], [2].Li-Fi utilizes light-emitting diodes (LEDs) for high-speed wireless communication and employs various modulation techniques to encode the signal. Common single-carrier modulation (SCM) schemes used in Li-Fi include on-off keying (OOK), pulse position modulation (PPM), and pulse amplitude modulation (PAM) [9]. However, as the data rate requirements increase in Li-Fi networks, SCM schemes such as OOK, PPM, and PAM may encounter issues like non-linear signal distortion at the LED front-end and inter-symbol interference caused by frequency selectivity in dispersive optical wireless channels. To overcome these challenges and achieve high-speed optical wireless communication, multi-carrier modulation (MCM) techniques are being explored. MCM is more bandwidth-efficient but less energy-efficient compared to SCM. One widely adopted MCM technique in Li-Fi networks is Orthogonal Frequency Division Multiplexing (OFDM) [10], [11]. In OFDM, parallel data streams are transmitted simultaneously using a set of orthogonal subcarriers, eliminating the need for complex equalization. An OFDM modulator can be implemented using an inverse discrete Fourier transform (IDFT) block, which is efficiently realized using the inverse fast Fourier transform (IFFT), followed by a digital-to-analog converter (DAC). As a result, the OFDM signal generated is inherently complex and bipolar. However, to comply with the intensity modulation and direct detection (IM/DD) requirements imposed by commercially available LEDs, certain modifications to conventional OFDM techniques are necessary in Li-Fi systems. These modifications ensure compatibility with the characteristics and limitations of the LED-based transmitters used in Li-Fi technology. To ensure a real-valued output signal after the inverse fast Fourier transform (IFFT), a commonly used approach is to enforce Hermitian symmetry on the subcarriers. Additionally, in Li-Fi, where light intensity cannot be negative, the signal needs to be unipolar. Several methods exist for obtaining a unipolar time-domain signal. One method is Direct Current biased optical OFDM (DCO-OFDM) [12], which employs a positive direct current (DC) bias to generate a unipolar signal. Although this approach increases the total electrical power consumption, it does not result in a loss of spectral efficiency. Another technique is Asymmetrically Clipped Optical OFDM (ACO-OFDM) [13], where only odd subcarriers are used for data transmission, while even subcarriers are set to zero, imposing Hermitian symmetry. As a result, the spectral efficiency of ACO-OFDM is halved. ACO-OFDM requires only a small DC bias, making it more energy-efficient compared to DCO-OFDM. Asymmetrically Clipped Direct Current biased OFDM (ADO-OFDM) [14] combines the DCO-OFDM scheme for even subcarriers and the ACO-OFDM scheme for odd subcarriers. In certain scenarios, ADO-OFDM demonstrates superior power-efficiency compared to both DCO-OFDM and ACO-OFDM. Another modulation scheme called Pulse-Amplitude-Modulated Discrete Multitone Modulation (PAM-DMT) [15] also clips the negative signal as in ACO-OFDM. However, PAM-DMT modulates only the imaginary parts of the signal on each subcarrier, ensuring that signal distortion resulting from asymmetric clipping affects the real component, which is orthogonal to the information-carrying signal. A hybrid optical OFDM scheme known as Asymmetrically Hybrid Optical OFDM (AHO-OFDM) [16] combines ACO-OFDM and PAM-DMT by utilizing both odd and even subcarriers for information transmission. These different modulation schemes, such as DCO-OFDM, ACO-OFDM, ADO-OFDM, PAM-DMT, and AHO-OFDM, offer various trade-offs in terms of power-efficiency, spectral efficiency, and signal distortion management, providing flexibility in adapting Li-Fi systems to different requirements and scenarios.

II. Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM In IM/DD Systems

The paper compares three forms of orthogonal frequency division multiplexing (OFDM) known as asymmetrically clipped optical OFDM (ACO-OFDM), DC biased optical OFDM (DCO-OFDM) and asymmetrically clipped DC biased optical OFDM (ADO-OFDM) In ACO-OFDM, the transmitted signal is modified by clipping the original bipolar OFDM signal at zero, transmitting only the positive parts, and utilizing only the odd subcarriers for data symbols [24]. DCO-OFDM, on the other hand, involves adding a

DC bias to the signal to ensure its positivity, with all subcarriers carrying data symbols. In terms of average optical power, ACO-OFDM outperforms DCO-OFDM for constellations like 4-QAM, 16-QAM, 64-QAM, and 256-QAM. However, for larger constellations such as 1024-QAM and 4096-QAM, DCO-OFDM is more efficient. This is due to the inefficiency of the DC bias used in DCO-OFDM in terms of optical power, while ACO-OFDM's utilization of only half the subcarriers for data transmission is inefficient in terms of bandwidth. ACO-OFDM delivers better overall performance for smaller constellations where optical power is crucial, while DCO-OFDM performs better for larger constellations where bandwidth is more significant. ADO-OFDM combines both ACO-OFDM and DCO-OFDM, using ACO-OFDM on odd subcarriers and DCO-OFDM on even subcarriers. The odd subcarriers are demodulated conventionally, while the even subcarriers undergo demodulation after an interference cancellation process. Analytical derivation of the probability density function (PDF) of optical and electrical power for transmitted ADO-OFDM signals indicates close agreement between simulated and theoretical PDFs. Simulation results also compare the optical power efficiency of ADO-OFDM with that of conventional ACO-OFDM and DCO-OFDM. The optical power in ADO-OFDM depends on the proportion of power allocated to ACO-OFDM, the DC bias level of DCO-OFDM, and the constellations sent on odd and even subcarriers. Plotting $(E_{b(opt)}/N_0)_{BER}$ against the proportion of optical power on ACO-OFDM reveals that smaller constellations like 4-QAM require a lower proportion of optical power on ACO-OFDM subcarriers to achieve the minimum $(E_{b(opt)}/N_0)_{BER}$ compared to larger constellations like 256-QAM. This is due to larger constellations necessitating a higher signal-to-noise ratio (SNR) for a given bit error rate (BER). Another plot of $(E_{b(opt)}/N_0)_{BER}$ against the proportion of optical power on ACO-OFDM shows the impact of varying the DC bias level on the DCO-OFDM component and the proportion of optical power allocated to ACO-OFDM. The plot indicates that, for a specific ADO-OFDM scheme, the proportion of optical power required on ACO-OFDM to achieve the minimum $(E_{b(opt)}/N_0)_{BER}$ is independent of the DC bias level. Moreover, increasing the DC bias level leads to an increase in the minimum value. Finally, the plot of $(E_{b(opt)}/N_0)_{BER}$ BER against the bit rate/normalized bandwidth demonstrates that ADO-OFDM achieves lower values compared to conventional schemes like ACO-OFDM and DCO-OFDM for bit rates/normalized bandwidths of 4, 5, and 6.

III. A Novel Technique to Simultaneously Transmit ACO-OFDM and DCO-OFDM In IM/DD Systems

This paper describes a new form of Orthogonal Frequency Division Multiplexing (OFDM) called Asymmetrically Clipped Optical OFDM (ACO-OFDM) and DC Biased Optical OFDM (DCO-OFDM) [23]. In this new system, ACO-OFDM is used on odd frequency subcarriers, while DCO-OFDM is used on even subcarriers. The received even subcarriers consist of four components: the desired DCO-OFDM signal, clipping noise from the transmitter's clipping of the DCO-OFDM signal, clipping noise from the transmitter's clipping of the ACO-OFDM signal (which affects only the even subcarriers), and channel noise. The clipping noise resulting from ACO-OFDM can be accurately estimated using a proposed technique, allowing for its subtraction from the DCO-OFDM component through interference cancellation before demodulation. This process doubles the effective Additive White Gaussian Noise (AWGN) power in the DCO-OFDM component, resulting in a 3 dB noise penalty. However, there is no clipping noise on the ACO-OFDM odd subcarriers in this new system, allowing for conventional demodulation. Simulation results show the constellation points of 4-QAM for different cases assuming no channel noise. The constellation diagram for 4-QAM ACO-OFDM indicates that the odd subcarriers remain unaffected, while the even subcarriers contain noise around the constellation points due to ACO clipping. Another constellation diagram for 4-QAM ACO-OFDM demonstrates that both the odd and even subcarrier constellation points have slight deviations from the ideal points, indicating clipping affecting all subcarriers. Higher DC bias levels result in smaller deviations. Two additional constellation diagrams are presented to illustrate the arrangement of constellation points for the proposed new technique (ADO-OFDM) before and after the cancellation of ACO-OFDM clipping noise on the even subcarriers. A Bit Error Rate (BER) versus Electrical Signal-to-Noise Ratio $(E_{b(elec)}/N_0)$ plot is shown for conventional ACO-OFDM, DCO-OFDM, and the new combined ACO-OFDM and DCO-OFDM technique. The 4-QAM, 16-QAM, 64-QAM, and 256-QAM curves are the same for both ACO-OFDM cases, indicating no interference caused by the DCO-OFDM carrying subcarriers on the ACO-OFDM subcarriers. The BER curves of the DCO-OFDM component in the new technique are 3 dB worse than the original DCO-OFDM curves due to the subtraction of even clipping distortion. Additionally, a BER versus Optical Signal-to-Noise Ratio $(E_{b(opt)}/N_0)$ plot is provided, demonstrating that the BER curves of the new scheme outperform conventional schemes in specific scenarios.

IV. Asymmetrical Hybrid Optical OFDM for Visible Light Communications with Dimming Control

The paper proposed an asymmetrical hybrid optical orthogonal frequency division multiplexing (AHO-OFDM) scheme for dimmable visible light communication systems [22]. The proposed scheme combines ACO-OFDM signals on odd subcarriers and PAM-DMT signals on even subcarriers in the time domain, with one of the signals inverted. This combination results in asymmetrical AHO-OFDM signals, where the powers of positive and negative signals are unequal. Dimming control is achieved by directly adjusting the amplitude of the combined signals, eliminating the need for PWM signal and reducing implementation complexity. Mathematical equations are derived for this scheme. The average amplitude of the combined AHO-OFDM signal is proportional to the average optical power of LEDs, as the AHO-OFDM signal's amplitude modulates the instantaneous power of the optical emitter. However, the amplitude of the combined AHO-OFDM signal is limited by the dynamic range of LEDs. If it exceeds this range, undesirable clipping distortion occurs. The extent of this distortion depends on the scaling factors of ACO-OFDM and PAM-DMT. When the scaling factors are sufficiently large, the probability of clipped signals becomes small, suppressing clipping distortion. However, a large scaling factor leads to low effective power at the receiver, degrading system performance. Hence, there is a trade-off between effective power and clipping distortion to achieve the desired bit error rate (BER) performance. When the scaling factors and dimming level are known, the required DC bias can be calculated mathematically. Simulation results demonstrate that the proposed scheme achieves a wide dimming range (10% to 90% when scaling factors are set to 4). By increasing the scaling factor, this range can be further expanded, albeit with lower effective power. The proposed AHO-OFDM outperforms DCO-OFDM and HACO-OFDM in terms of supporting a broader dimming range. Additionally, its achievable spectral efficiency remains relatively stable as the dimming level varies. The proposed scheme exhibits higher power efficiency when the desired dimming level is either very high or very low.

V. Hybrid DCO-OFDM, ACO-OFDM and PAM-DMT For Dimmable LIFI

HDAP-OFDM is a hybrid modulation scheme that combines three OFDM formats: DC-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), and pulse amplitude modulated discrete multitone (PAM-DMT) [21]. In HDAP-OFDM, the lower-index subcarriers carry DCO-OFDM, while the higher subcarriers carry ACO-OFDM on odd-index subcarriers and PAM-DMT on even-index subcarriers. The integration of these three elements introduces interference among them. At the receiver, the clipping noise resulting from ACO-OFDM and PAM-DMT is estimated and subtracted from the composite signal to obtain the DCO-OFDM component. To ensure a unipolar combined signal, a complex function of scaling factors from the three individual components and LED limitations is used to determine the DC bias term (I_{Bias}). By adjusting the values of IBias, different dimming levels can be achieved, and increasing the scaling factors widens the dimming range in HDAP. To evaluate the performance of HDAP-OFDM in Li-Fi systems, simulations were conducted using MATLAB, considering an ideal additive white Gaussian noise (AWGN) optical channel without additional distortions. The peak-to-average power ratio (PAPR) of HDAP-OFDM is higher than that of AHO-OFDM but lower than DCO-OFDM and other OFDM techniques. The inclusion of the DCO-OFDM component in HDAP-OFDM leads to a larger PAPR compared to AHO-OFDM. Therefore, the nonlinearity issue of LEDs is more significant in HDAP-OFDM than AHO-OFDM but less critical than DCO-OFDM. By adjusting the power level of the individual elements in HDAP-OFDM, the bit error rate (BER) performance can be improved compared to AHO-OFDM. BER versus E_b/N_0 plots demonstrate that at a target BER of 10^{-3}, HDAP-OFDM outperforms AHO-OFDM by 7 dB but lags behind DCO-OFDM by 8 dB. The comparison of ($E_{b(elec)}/N_0$) versus bit rate/normalized bandwidth reveals that for a specific BER and a bit rate/normalized bandwidth of 2 or 3, HDAP-OFDM requires lower ($E_{b(elec)}/N_0$) than AHO-OFDM. The power efficiency of the DCO-OFDM element in HDAP contributes to the system's performance improvement, as increasing its proportion enhances HDAP's performance. Furthermore, the effectiveness of HDAP-OFDM for dimmable Li-Fi is evaluated. Dimming in HDAP-OFDM is achieved by adjusting the constellation size and the level of DC bias. An algorithm is presented to describe the dimming flexibility of HDAP-OFDM. Bit rate/normalized bandwidth versus dimming levels demonstrates that both AHO-OFDM and HDAP-OFDM support a wider dimming range compared to DCO-OFDM. HDAP can achieve a dimming range of 3% to 97%, which is similar to that of AHO-OFDM. Notably, for a dimming range of 10% to 90%, HDAP exhibits a better achievable bit rate/normalized bandwidth compared to AHO-OFDM. Although HDAP-OFDM introduces greater implementation complexity than ACO-OFDM, DCO-OFDM, and AHO-OFDM due to the need for multiple inverse fast Fourier transform (IFFT) operations at the transmitter and receiver, it is feasible to develop transmitter and receiver systems.

VI. A Novel OFDM Format and A Machine Learning Based Dimming Control For LIFI

A new hybrid form of orthogonal frequency division multiplexing (OFDM) called DC-biased pulse amplitude modulated optical OFDM (DPO-OFDM) was proposed in this paper. This new format combines the concepts of existing DC-biased optical OFDM (DCO-OFDM) and pulse amplitude modulated discrete multitone (PAM-DMT) [19]. In DCO-OFDM, the odd subcarriers are modulated, while in PAM-DMT, the imaginary part of even subcarriers is modulated. DCO-OFDM requires a DC bias (referred to as I_{Bias}) in the paper to convert the composite signal into a unipolar signal, as the intensity of light cannot be negative. The paper derives mathematical expressions for the DC-bias level in the proposed DPO-OFDM. I_{Bias}, depends on the scaling factor of the individual components of the technique, as well as $I_L$and I_H (high and low intensities of the light source). By adjusting the value of I_{Bias}, different dimming levels can be achieved. The paper compares the bit error rate (BER) performance and spectral efficiency of DPO-OFDM with dimming control to existing optical OFDM formats using the MATLAB tool. The results show that both DPO and DCO have excellent efficiency in terms of electrical energy per bit to noise power spectral density ($E_{b(elec)}/N_0$). For a bit rate/normalized bandwidth (denoted as R) of 2, 3, and 4, DPO requires a lower electrical energy per bit to noise power spectral density ($E_{b(elec)}/N_0$) than HDAP and AHO, considering a BER of 10^{-3}. However, for the same values of R, DPO requires a lower electrical energy per bit to noise power spectral density ($E_{b(opt)}/N_0$) than AHO, but higher than ADO. The paper also investigates the effect of the number of OFDM subcarriers on the BER performance for different OFDM formats in an AWGN channel and finds that the BER performance remains unchanged with varying numbers of subcarriers. The paper further examines the dimming range performance of DPO, HDAP (50% DCO and 50% ACO-PAM), AHO, DCO, and ADO with respect to R. It is found that DPO provides a better R for the dimming range of 40-60% compared to other OFDM techniques, indicating that DPO is more optically power-efficient in this case. The paper proposes a switching algorithm for the existing HDAP-OFDM, where the individual components of HDAP-OFDM are switched based on a target dimming level. MATLAB tool is used for simulation. A light sensor at the transmitter section monitors the ambient light and its changes to calculate the dimming level. The suitable scheme from ACO-PAM (2-10% or 90-98%), HDAP (10-30% or 70-90%), and DCO (30-70%) is selected by the scheme selection block to achieve a wide dimming range with better spectral efficiency. The utilization of machine learning regressors allows for the determination of the appropriate constellation size of either DCO or PAM-DMT, one component of DPO, given the other component and the known target dimming level. To generate the dataset, the DPO-based LiFi system was simulated using the MATLAB tool. The dataset consists of input attributes such as the subcarrier number N, the number of symbols, the constellation size of the PAM-DMT element denoted as M_PAM, and the dimming level. The target attribute of the dataset is the constellation size of the DCO element denoted as M_DCO. While the linear regression model did not yield satisfactory results for the dataset, polynomial regression of degree 4 exhibited a better root-mean-square error (RMSE) compared to degrees 2, 3, 5, and higher. This concept is also applicable to HDAP-OFDM and other hybrid OFDM formats.

VII. Machine Learning For DCO-OFDM Based LIFI

In DCO-OFDM, a DC bias is utilized to convert the bipolar signal into a unipolar signal. However, determining the optimal DC bias value poses a challenge. A large bias value results in optical power inefficiency, while a small bias value introduces higher clipping noise. This paper proposes the application of machine learning (ML) algorithms to identify the ideal DC bias value for DCO-OFDM-based Li-Fi systems, as selecting an appropriate DC bias is crucial [20]. A MATLAB tool is employed to generate a dataset for DCO-OFDM systems. The generation of DCO-OFDM signals relies on various parameters, including the constellation size (M) denoting the number of bits per symbol and the energy per bit to noise spectral density E_b/N_0. Through MATLAB simulations, the dataset collects mean, minimum, maximum, standard deviation, bit error rate (BER) values, constellation size (M), and subcarrier number (N). Python programming language, along with Numpy, Panda, and Seaborn libraries, is utilized to apply machine learning algorithms to the dataset, seeking the most suitable algorithm for the problem domain. The input attributes consist of M, N, the target BER, and the mean, minimum, standard deviation, and maximum values of the transmitted OFDM signal. The output attribute is set as the DC bias value. For linear regression, the most important features are selected using a univariate feature selection method. For the best five features, notably higher training and testing accuracy are achieved. Performance declines when considering fewer than five features. Among the five features, polynomial regression with a degree of 2 or 3 exhibits comparable performance, yielding R2 scores around 0.95. However, when considering six or seven features, polynomial regression with a degree of 2 outperforms others, showcasing a high R2 score for test sizes of 0.1, 0.2, and 0.3. The authors illustrate the effectiveness of both linear regression and polynomial regression by plotting the actual and predicted DC bias values for different numbers of features. While both linear and polynomial regression can be employed to determine the appropriate DC bias for DCO-OFDM, the polynomial regression model proves more reliable in predicting the DC bias value for DCO-OFDM-based Li-Fi systems.

VIII. Conclusion

This report presents a theoretical study of various modulation techniques used in OFDM-based Li-Fi systems, drawing from relevant literature. It is important to note that no simulations have been conducted to validate the claims made by the authors. Moving forward, the focus of future work will revolve around introducing a novel form of OFDM technique aimed at addressing the current limitations.

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