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Visible light communication using new Flip-FBMC modulation system technique

Abdullah Ali Qasim[1], Husam Noman Mohammed Ali[2], Ali Kadhim Obaid[3], M. F. L Abdullah[4], R. Talib[5], M. S. M Gismalla[6], Wafi A. Mabrouk[7]
[1,4,5,6,7]Communication Engineering Department, University Tun Hussein Onn Malaysia, Johor, Malaysia
[1,2,3]Engineering Technical College-Najaf, Al-Furat Al-Awsat Technical University, Najaf, Iraq
[6]Department of Electronics and Electrical Engineering, Faculty of Engineering, International University of Africa (IUA), Khartoum, Sudan

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ABSTRACT

Filter bank multi-carrier (FBMC) modulation in the visible light communication (VLC) system is one of the most promising modulation systems in optical wireless communications (OWC), especially in 5G and 6G future applications. FBMC has a wide bandwidth compared to other modulation systems. One of the highest degree essential conditions for utilising the signal in VLC is that the signal is real positive, the signal is agreeable with intensity modulation/direct detection (IM/DD), where Hermitian symmetry (H.S) is utilised to get a real signal (RE) and to be unipolar direct current (DC)-bias is used. Here the challenge arises as this method increases complicating, due to the modulation of the N number of frequency symbols, these symbols need 2N inverse fast fourier transform (IFFT) and fast fourier transform (FFT), in addition to energy consumption. This research focused on the time domain and not the frequency domain by using the traditional complex FBMC generation signal, and to obtain the RE signal by placing the RE signal side by side with the imaginary signal (IMs) in a row, and then using new Flip-FBMC technology, which saves more energy. The proposed technologies provide approximately 57% of the number of IFFT/FFT. The use of Flip-FBMC technology consumes less energy than traditional technologies with better bit error rate (BER) performance.

Corresponding Author:

Abdullah Ali Qasim
Communication Engineering Department
University Tun Hussein Onn Malaysia
Johor, Malaysia
Email: alzubydea@gmail.com, alzubydea@atu.edu.iq

1. INTRODUCTION

High technological development in using mobile devices has increased the demand for high capacities which has made the radio frequency (RF) communication system a big problem because of its narrow bandwidth [1], [2]. Therefore, scientists have turned to the optical wireless communication (OWC) system, especially visible light communication (VLC) because it has a large unlicensed bandwidth, making it a suitable alternative to the RF system, especially for indoor environments where it is harmless [2], [3]. Solid-state semiconductor light (SSL), whether light-emitting diode (LED) or laser diode (LD) [4], is the main factor in the evolution of optical communications as it provides several benefits including increased efficiency and long lifetime with a large bandwidth and less power consumption [3]-[5]. All these characteristics add sufficient visibility to the exploitation of its major function besides illumination in communications [6]. VLC has become one of the to the highest degree promising candidates for wireless communications for indoor environments in the upcoming 5G fifth-generation communications [7]. Recent research has made it very promising to the 6G sixth-generation of wireless communications. Since VLC transmits high bandwidth, this serves to solve the problem of the growing demand for great bandwidth in telecommunication networks, whether 5G or 6G [7]-[12]. Orthogonal frequency division multiplexing (OFDM) is one of the active techniques in communication systems due to its power efficiency, bandwidth, flexible, and many features [11]. Using OFDM in radio wireless communications is mainly a complex signal, compared to optical wireless communication, intensity modulation/direct detection (IM/DD) meaning the signal is a real signal (RE) and positive [13]. When designing the OFDM signal to be IM/DD compatible, it should be a RE positive. To obtained a RE signal, several techniques are commonly used, most notably the Hermitian symmetry (H.S) technique, which excludes the imaginary signal (IMs) and passes the RE signal [13]-[16]. There are several forms of the OFDM system for it to be positive, such as the asymmetrical clipped optical OFDM (ACO-OFDM) [17], [18], direct current (DC)-bias optical OFDM (DCO-OFDM) [17], [19], Flip-OFDM [16], [20], and other forms. Although OFDM is efficient, it has several drawbacks that make it inefficient to work within the VLC system, therefore, a suitable alternative need to be found. The primary weakness of OFDM modulation is its high spectral leakage because of rectangular windows. There is also weak spectral efficiency due to the cyclic prefix (CP) besides interference between asynchronous signals [6], [21].

Filter bank multi-carrier (FBMC) is an appropriate alternative which takes all the advantages of OFDM modulation and overcomes all OFDM disadvantages by adding pulse shape filters which produce a local sub-channel well in both the time domain and frequency field. FBMC does not use CP [22], so it has high spectral efficiency and a very low side loop. Recent research has begun to develop this system for it to work in optical communications, especially in the field of VLC which has used several techniques [23]-[25]. One of the most prominent of these techniques used to get a RE signal is the H.S technique, but this technique increases the complexity of the IFFT/FFT systems. Barrami *et al.* [26] proposed an alternative technique for this technique in OFDM to address this weakness or to improve.

In this research, the focus was on the time domain as the complex signal is separated into RE and IMs, changes the IMs to RE, and then sent them sequentially. This technique reduces complexity and ensures that the signal is RE without spectral efficiency losses. To ensure that the signal is IM/DD compatible, it must be unipolar and in the conventional way, DC-bias is added. However, to the best of our knowledge, this is the first time a modern Flip-FBMC approach has been used. This technique saves more power than DC-bias at same spectral efficiency. This paper provides the main contributions for the VLC system; reviews the improvement and analysis of the obtained RE signal; proposes a new Flip-FBMC technology to generate a unipolar signal; and performs a performance comparison between the new technology and conventional technology.

2. REAL TIME FBMC SIGNAL FOR VLC SYSTEM

As mentioned above, the optical signal must be 100% compatible with IM/DD, and thus be subject to two main conditions: first, the signal is RE and not complex, and the second is that the signal is a positive unipolar. The following methods explain how to obtain the RE signal: the first conventional method involves the use of H.S and the second method adopted in this research found that there was a big difference between the two methods.

2.1. Hermitian symmetry

Figure 1 shows the transmitter block diagram of the FBMC system in the VLC using H.S where the system focuses on the frequency domain. Note that the prototype filters out of the offset QAM (OQAM) signal will be complex ($a + jb$), characterized by the overlap factor K, which represents a number of multi-carrier symbols that overlap in the time domain. To get a RE sub-carrier, input frequency symbols must be constrained to the IFFT block by using the H.S [25], [27]-[29]. This means that to modulate and demodulate the N frequency symbols, 2N number symbol sub-carriers IFFT/FFT are required to obtain a RE signal with the double of the circuit complexes that meaning 50% loss as shown in Figure 1 as well as in (1) [6], [13], [23], [24], [26], [30], [31]:

$$X_{2Lp} = [X_0, X_1, X_2, \dots \dots, X_{LP-1}, X_{LP}, X^*_{LP-1}, \dots . X^*_2, X^*_1] \quad (1)$$

where X is the frequency symbol, N is the number of sub-carriers, and (*) denotes the complex conjugation. The two components X_0 and X_{Lp} were set to zero because the H.S uses inputs [28], [32]-[35]. The signal from the IFFT after being converted from the frequency domain to the time domain, x_n, is RE and not complex with a length of $2Lp$, where $Lp = K * N$. The discrete-time signal at the IFFT output is set by:

$$x(n) = \sum_{n=-\infty}^{+\infty} \sum_{m=0}^{2N-1} a_{m,n} g_{m,n}(t) \quad (2)$$

where $a_{m,n}$ is the RE symbol denoting transmitted, the sub-carrier index is denoted by the letter n, m is the time index ; and $g(t)$ is the synthesis function whom maps $a_{m,n}$ into the signal space. $g_{m,n}(t)$ is the time and frequency shifted version, and τ_0 is the symbol interval in time [36].

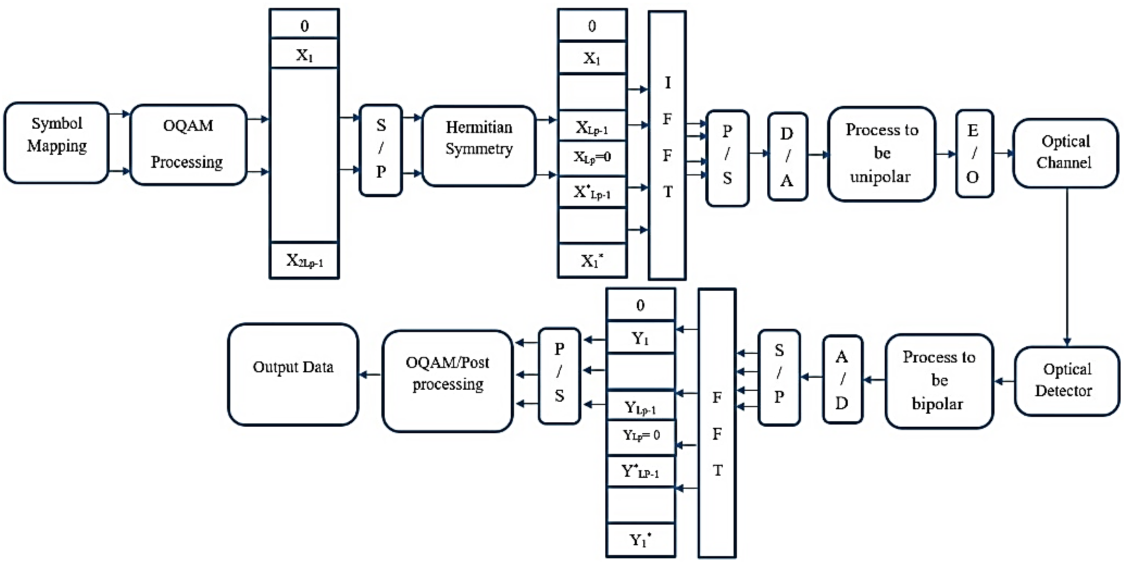

Figure 1. Block diagram of optical FBMC modulation by using H.S

2.2. New imaginary to real conversion technique (I2R-CT)

As mentioned, the optical signal must be RE, and to get it, it is necessary to apply a technique that switches a complex signal into a RE signal. H.S was used, but because of the increase in complexity, this challenge led to encouragement to discover another way to obtain RE signal without using H.S, so a new technique was set up with FBMC to generate a RE signal and focused the technique on the time domain [31] as shown in Figure 2. The RE signal which was bipolar converted to the unipolar using techniques that will be mentioned later and the signal was sent and received by the optical detector and then the signal analyzed as shown in Figure 2. The output signal from IFFT passed through parallel to the serial converter (P/S) and the signal at this stage is a complex signal ($a + jb$), which is similar for a signal from FBMC conventional, meaning that it is incompatible with IM/DD. Therefore, the complex signal must be changed into a RE signal, by separating the RE signal from the IMs and then turning it into a RE signal. Then, the RE signal placed side by side with the IMs, and they are sent together.

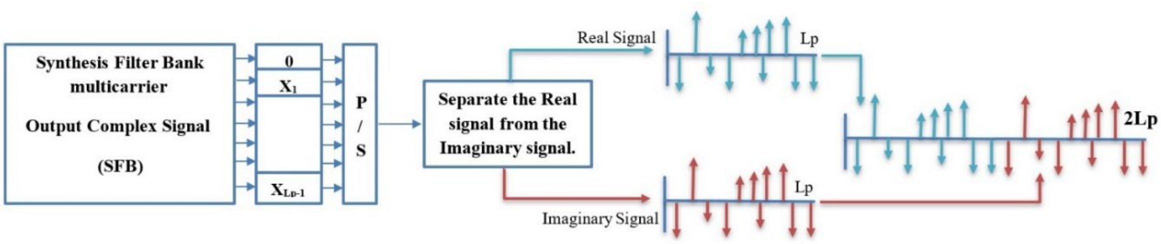

Figure 2. New optical FBMC transmitter modulation using N points IFFT

This technique that uses N-points to get a RE signal without the use of H.S [37], as observed in (3) shows that the signal coming out of IFFT is a complex signal and is not processed.

$$x(n) = \sum_{n=-\infty}^{+\infty} \sum_{m=0}^{N-1} a_{m,n} g_{m,n}(t) \tag{3}$$

Since this technique focuses on the time domain, $x(n)$, is still a complex signal as in (4).

$$x(n) = a(n) + jb(n), \;\; n = 1,2,3, \dots .(Lp-1) \tag{4}$$

a and *b* denote the RE and IMs signal components in the time domain *x(n)*, where the length of both the RE part and the IMs is *Lp* points when separated is as shown in Figure 3. Then, the RE signal at *Lp* points is placed side-by-side to *Lp* points IMs as in (5). These steps are important in generating a RE signal with a length of *2Lp*.

$$x_{2Lp} = \begin{cases} a(n) & n = 0, \dots.., Lp-1 \\ b(n-Lp) & n = Lp, \dots..,2Lp-1 \end{cases} \tag{5}$$

Figure 2 and Figure 4 show the shape of the output signal after implementing the technique. After completing all the steps, a RE signal emerges, but is bipolar so it is converted by one of the techniques to be unipolar and compatible with IM/DD. After receiving the optical signal through the optical detector, it passes through several stages to return it again to bipolar to begin the process of analysis of the received signal. Figure 5 illustrates the block diagram of the receiving system that analyzes the signal by re-separating the RE part from the IMs part as in (6).

$$y(n) = \begin{cases} a_r(n) = y_{2Lp}(n), & n = 0,.,Lp-1 \\ b_r(n) = y_{2Lp}(Lp+n) & n = 0,..,Lp-1 \end{cases} \tag{6}$$

ar and *br* are the received RE and IMs parts respectively of the received signal *y(n)*. After this stage, the complex signal is re-shaped again and completes the demodulated signal process as in the convolution FBMC modulation.

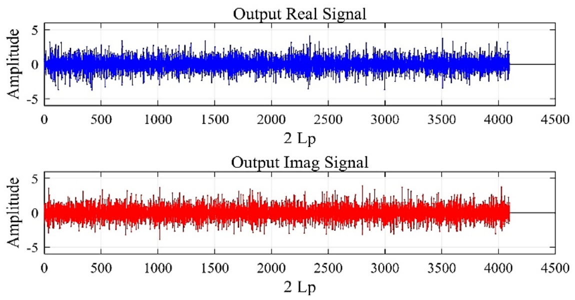

Figure 3. RE and IMs after separated

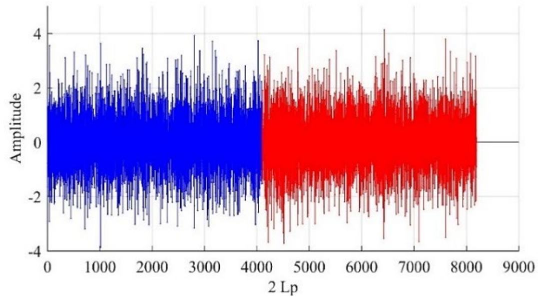

Figure 4. The proposed output signal optical FBMC modulation RE signal by using new I2R-CT

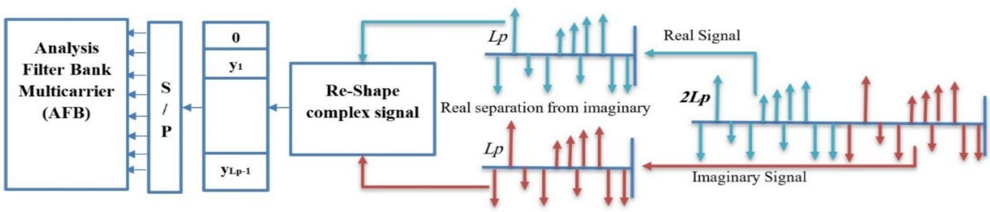

Figure 5. Block diagram of optical FBMC new I2R-CT receiver

3. UNIPOLAR FBMC MODULATION TECHNIQUE

After extracting the RE signal in the time domain, the signal is bipolar, and to make this signal compatible with IM/DD, it must be made unipolar, so the DC bias technique was used, but this technique, as mentioned previously, consumes additional power, so in this paper, Flip-FBMC technology was proposed, to convert the signal from bipolar to unipolar. The working method of the conventional DC bias technique and the proposed technique will be explained below.

3.1. DC-bias FBMC modulation

DC-bias is one of the most important techniques used with the modulation for signal unipolarity without loss of spectral efficiency and still works in the modulation systems, as in OFDM was also used and in the FBMC modulation system [16], [25], [36]. In DCO-FBMC modulation, DC-bias were added to obtain the unipolar signal for high Lp, the $x(n)$ signal canful be modulated into a Gaussian random variable with mean zero and variance $\sigma_n^2 = \{E[x_n^2]\}$. The negative peaks in the signal should clip first. Therefore, a suitable DC-bias is added to the $\boldsymbol{x_n}$ signal to remove negative peaks. This, in turn, adds clipping noise, and when DC-bias is high level, this noise decreases and affects all sub-carriers.

$$x_{dc} = x_n + B_{dc} + n_c \tag{7}$$

$\boldsymbol{x_{dc}}$ is the unipolar signal after adding DC-bias, x_n is the bipolar signal, B_{dc} and n_c are the DC-bias and clipping noise respectively. When the DC-bias becomes large, the clipping noise is neglected.

$$x_{dc} = x_n + B_{dc} \tag{8}$$

The value of DC-bias is calculated to be set proportional to the power x_n.

$$B_{dc} = K_b \sigma_n \tag{9}$$

K_b is the clipping factor and can be calculated as:

$$K_b = \sqrt{10^{R/10} - 1} \tag{10}$$

where R is the is the bias level in dB. There is no necessity to set an optimal bias level for different modulation commands. The increase in the level of bias leads to two points; the first is to increase power consumption, and the second reduces clipping noise. When there is a high-level bias, noise clipping will be neglected or virtually non-existent as in (8) and then SNR_{ele} for a given bit error rate (BER) is relatively equal to the value of SNR_{ele} for bipolar signal [13]. As shown in Figure 6, after the optical signal is transmitted and received by the optical receiver, the effect of DC-bias is removed and the signal returns as a bipolar signal.

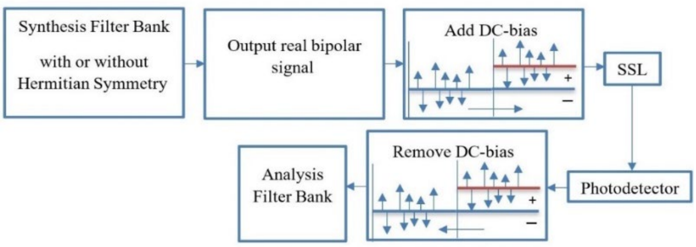

Figure 6. DCO-FBMC block diagram

3.2. Flip-FBMC modulation

Unipolar communication systems can transmit data by RE and positive signals, such as optical communications, especially the VLC system. VLC modulation systems should be simple and fast because they have high bandwidth, so modulation systems should be fast without spectral efficiency losses and do not consume power. The block diagram in Figure 7 illustrates the Flip-FBMC modulation which is presented for the first time in this paper.

Flip-FBMC in the time domain of the RE signal was obtained without the use of the H.S, as previously explained. The shape of the RE signal after exiting synthesis filter bank (SFB) is as shown in Figure 4 since it is bipolar. This technique does not use DC-bias to convert the signal to unipolar. This technique works on the main signal coming out in (5), where the signal was bipolar, so the first steps that were decomposed to separate the positive signal from the negative signal.

$$x_{2Lp} = x_{Lp}^{+} + x_{Lp}^{-} \tag{11}$$

x_{2Lp} is a RE bipolar signal, x^+_{Lp} is the positive part separated from the x^-_{Lp} negative part in the signal. The positive and negative parts of the signal are defined as follows:

$$x^+_{Lp} = \begin{cases} x^+_{Lp} & x_{2Lp} > 0 \\ otherwise = 0 \end{cases} \tag{12}$$

$$x^-_{Lp} = \begin{cases} x^-_{Lp} & x_{2Lp} < 0 \\ otherwise = 0 \end{cases} \tag{13}$$

The negative signal is inverted to a positive signal by the inverter and then combined with the first positive part. Then, the signal is transmitted through the laser, as shown in Figure 8, which shows the shape of the signal transmitted to one frame. The transmitted signal will be a RE unipolar positive and thus the two conditions will be met to be IM/DD compliant. After the signal is sent from the optical transmitter, it will be received by the optical receiver, where the light signal is changed into an electrical signal and then the signal is dismantled into two parts. The second part (which is originally negative) is flipped back to its original shape, after which the first part (positive signal) is consolidated with the second part (negative signal), and this bipolar signal is restored.

$$y_{2Lp} = y^+_{Lp} - y^-_{Lp} \tag{14}$$

where y^+_{Lp} and y^-_{Lp} represent the positive and flipped second part, respectively. The complete signal process after the restoration of a bipolar signal has already been explained.

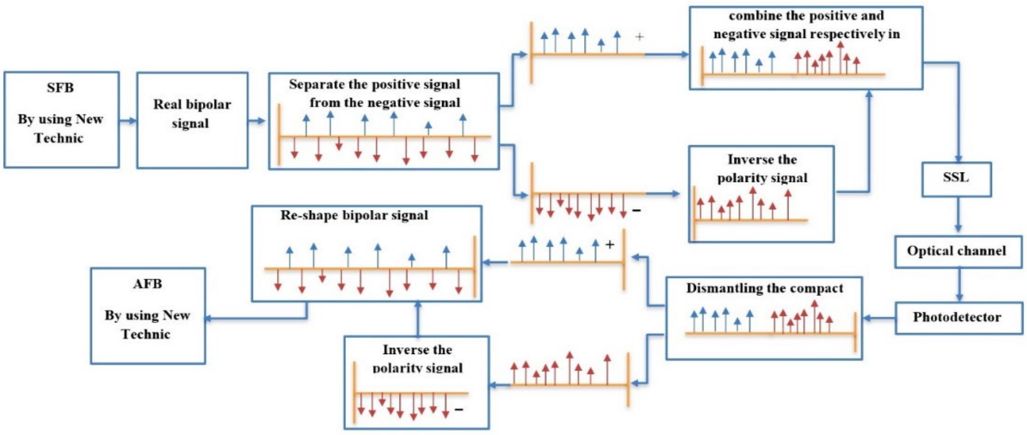

Figure 7. Flip-FBMC modulation system block diagram

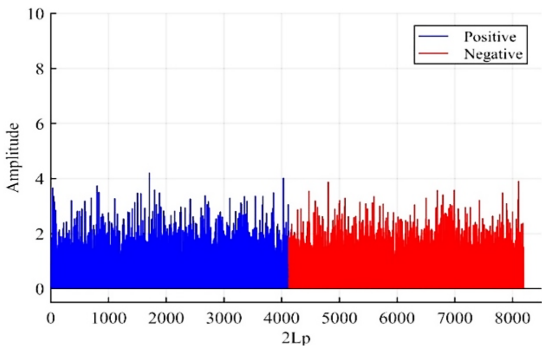

Figure 8. Flip-FBMC modulation transmitter signal

4. CALCULATION AND RESULTS

In this paper, the results of the proposed techniques were highlighted to reduce complexity and consuming power, which effectively contributes to raising the performance of the VLC system. The most important BER results, complexity and consumable capacity of the proposed techniques are given below:

4.1. BER performance

BER is one of to the highest degree important factors for an evaluation of the system. Figure 9 shows that BER is a function of SNR in dB. The new technique and conventional technique (using H.S), used DCO-FBMC, 4QAM, 16QAM, 64QAM, and 256QAM. As in Figure 9, N-points IFFT/FFT for the new technique and 2N-points IFFT/FFT for the conventional technique were used. The SNR performance of modern technology is identical to that of conventional technology.

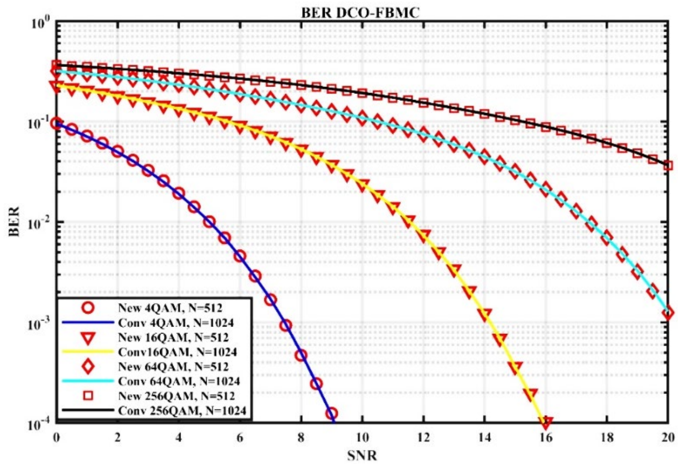

Figure 9. BER was a function of SNR of the conventional (Conv) DCO-FBMC and new technique DCO-FBMC in different M-QAM

4.2. FFT/IFFT implementation complexity

The new technique uses half the size of FFT/IFFT, so when calculating, the complexity is determined as the number of multiplication and additions as in Figure 10 and Figure 11. The two figures illustrate the main comparison between the techniques calculated in (15), (16), (17), and (18) for the transmitter depending on [38], [39]. The complexity in FFT/IFFT as well as the spectral efficiency losses were reduced. The new technology was tested with the traditional technique in obtaining a RE signal using DC-bias technology to be unipolar and IM/DD compliant.

$$C_{new} = N\left(log_2\left(N/2\right) - 3\right) + 8 + 4(NK + 1) \quad (15)$$

$$C_{con} = 2N(log_2(N) - 3) + 8 + 4(2NK + 1) \quad (16)$$

$$A_{new} = 3N\left(log_2\left(N/2\right) - 1\right) + 8 + 4(NK - N + 1) \quad (17)$$

$$A_{con} = 6N(log_2(N) - 1) + 8 + 4(2NK - 2N + 1) \quad (18)$$

Using operating equations, the complexity was calculated for each bit that was saved when using the new method and conventional method. The way to calculate the complexity of the new method is in (19) and (20) for the convolution method.

$$New = N\left(log_2\left(N/2\right) - 3\right) + 8 + 4(NK + 1) + 3N\left(log_2\left(N/2\right) - 1\right) \\ +8 + 4(NK - N + 1) \quad (19)$$

$$Conv = 2N(log_2(N) - 3) + 8 + 4(2NK + 1) + 6N(log_2(N) - 1) \\ +8 + 4(2NK - 2N + 1) \quad (20)$$

Then, to calculate complexity saving (GA) was calculated through the following;

$$GA = \left[1 - \frac{New}{Conv}\right] \times 100\% \quad (21)$$

According to Figure 12, it can be seen that the computational complexity of each bit of savings dropped slowly with the size of (I) FFT, and was eventually 50% when (*N*=4096 and *2N*=8192), and 57.62% when (*N*=32 and *2N*=64).

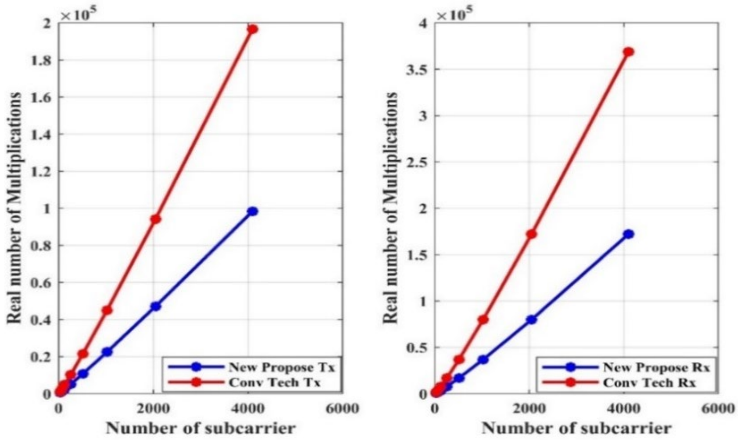

Figure 10. The number of multiplications between the I2R-R2I-CT and the H.S technique in: (a) transmitter and (b) receiver (Rx)

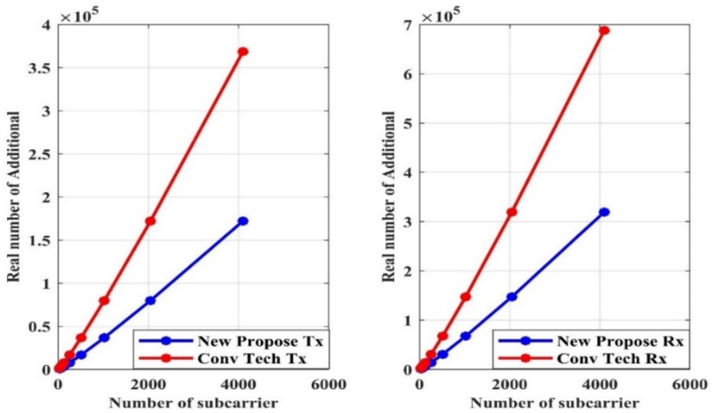

Figure 11. The number of additional between the I2R-R2I-CT and the H.S technique in transmitter (Tx) a receiver (Rx)

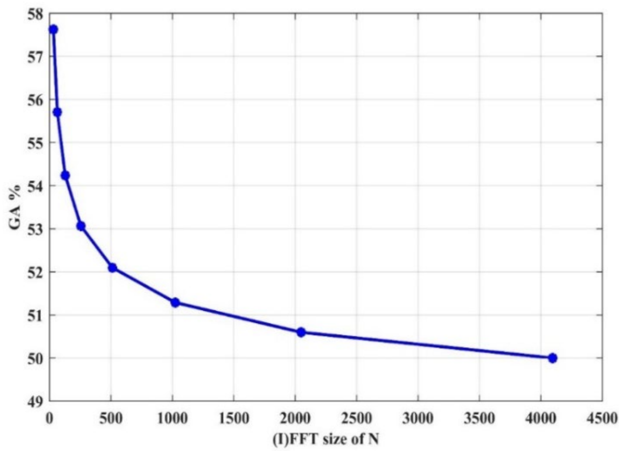

Figure 12. The computational complexity of each bit savings

4.3. Comparison between Flip-FBMC and DC-FBMC

The RE signal obtained by using the new method without the use of the traditional technique (H.S) was bipolar, but the signal must be RE and positive i.e. is unipolar to be compatible with IM/DD. As shown in Figures 6 and 7, the design is different for both DCO-FBMC and Flip-FBMC, but the aim is to obtain a unipolar signal. The spectral efficiency of both techniques is the same as the spectral efficiency (the N-length channel is used in two techniques to transmit N information symbols), but there are some differences in terms of performance. From the above, the DCO-FBMC system consumes high power. For DCO-FBMC technology using $P_{opt} = E\ \{x_{2Lp}\}$ and $P_{elec} = E\ \{x^2_{2Lp}\}$ since B_{dc} is defined in (9), here under the assumption of efficient bias for the optical to electrical conversion efficiency is as follows:

$$\delta_{dc} = \frac{P_{elec}}{P_{opt}} \tag{22}$$

where for sufficient biasing in [13], [24], [30]

$$P_{opt} = B_{dc} \tag{23}$$

$$P_{elec} = \sigma^2_{x_n} + B^2_{dc} \tag{24}$$

So, the optical to electrical conversion efficiency can be calculated as in the following;

$$\delta_{dc} = \frac{\sigma^2_{x_n} + B^2_{dc}}{B_{dc}} \tag{25}$$

For fair comparison with modulation techniques including Flip-FBMC, P_{opt}=1. This normalization means B_{dc}=1, since $B_{dc}=K_b\ \sigma_{xn}$, where $\boldsymbol{\delta_{dc}}$ given as:

$$\delta_{dc} = \frac{1-K^2_b}{K^2_b} \tag{26}$$

In Figure 13, it is observed that δ_{dc} decreases with increasing B_{dc} value, so when B_{dc} increases, the optical power consumption in DCO-FBMC increases, which reduces signal distortion. The Figure 13 basically shows that DCO-FBMC has a high-power consumption compared to the Flip-FBMC modulation, and BER's performance in Flip-FBMC is better for different M-QAM as shown in Figure 14, which is slightly better than DCO-FBMC.

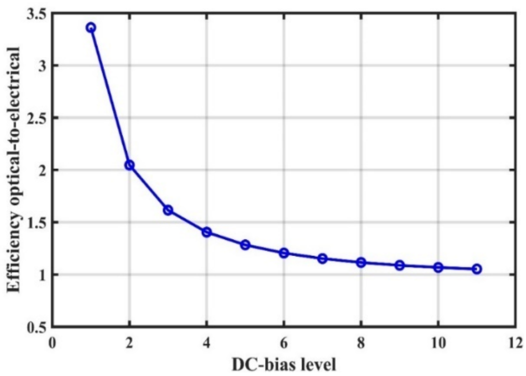

Figure 13. Electrical to optical efficiency δ_{dc} for different DC-bias level

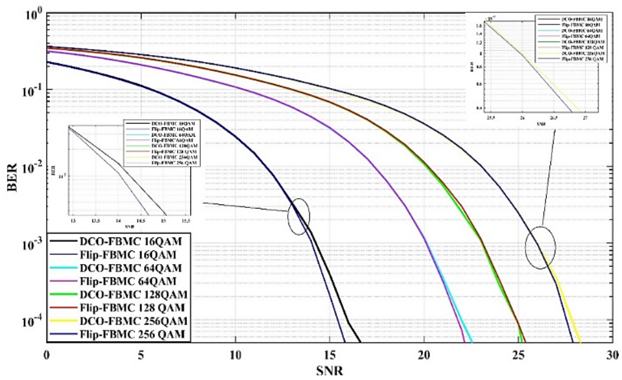

Figure 14. BER performance of Flip-FBMC vs DCO-FBMC

5. CONCLUSION

The visible light communication system is the next generation of communication in 5G and 6G as VLC has high bandwidth, so it was necessary to develop a modulation system in order to avoid any losses in spectral efficiency characterized by simplicity and speed besides little power consumption. The IM/DD signal was transmitted in the VLC system and is a RE positive. Therefore, a new technique was introduced to generate a RE signal without using H.S. The new technique did not suffer from an increase in complexity since they used N-point IFFT/FFT instead of 2N-point IFFT/FFT. They also saved bits 57.62%, thus also reducing power consumption. The authors of this study say that the proposed methodology achieves the same BER as traditional technology. In this paper, the Flip-FBMC technique was used to generate a unipolar signal by separating the positive signal from the negative signal and then flipping the negative signal and making it positive. The positive part was then merged with the negative part respectively, and the signal was then transmitted with one frame. This method is uncomplicated and fast and does not consume power unlike the conventional method that uses DCO-FBMC. Note that BER performs better than conventional technology.

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