Adaptive DCO-FBMC in Visible Light Communication

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Abstract. Filter Bank multicarrier (FBMC) has been modified for VLC. FBMC is the main filter suitable for high-speed data transfer using multicarrier modulation (MCM). Therefore, the FBMC is an appropriate alternative to the OFDM system which suffers from several weaknesses like limited bandwidth due to the presence of the cyclic prefix (CP). FBMC has been adapted to IM / DD compliant using Hermitian Symmetry to make the real signal, but this method increases system complexity and power consumption. In this paper, FBMC was adapted using a different technique than the above which consisted of generating an original complex FBMC signal. The signal was then dismantled into two real and imaginary parts (juxtaposing the real and imaginary parts of the complex signal in the time domain), thus the imaginary signal turned real. The proposed technique saved 50% in the number of the FFT/IFFT (Inverse Fast Fourier Transformer/ Fast Fourier Transformer) operations, which resulted in a great decrease in power consumption and the occupied chip area.

1. Introduction

The significant development in solid-state light-emitting diodes (LED or LD) began when it was used in luminance at a large level inside buildings and outdoors [1] due to its high luminance efficiency, low cost, low power consumption compared to other types of illumination and long life. The speed of switching that has been used in digital communication as it is harmless to the human eye [2]. Optical communications have attracted the attention of many researchers, especially the VLC system because of the use of visible light, which has an unlicensed spectrum with a wide range of (400nm-800nm) in addition to this type of communication. The VLC system with a large unregulated spectrum is an excellent alternative to the limited spectrum of RF [3].

Orthogonal frequency division multiplexing (OFDM) is popularly employed in high data rate communications because of its capacity to combat inter-symbol interferences (ISI) [4]. However, the signal from OFDM cannot be used in intensity modulation / direct detection (IM / DD) systems because it is complex and bipolar, and the electrical signal is modulated on the transmitter. The Hermitian Symmetry technique is used to obtain a real signal in the system where the incoming symbols are restricted to inverse Fast Fourier transform (IFFT) at which the imaginary signal is excluded [5]. The signal emerging to be compatible with the IM / DD system must be positive and non-negative. This is done by applying DC-Bias technology to make sure it is not negative i.e. unipolar. This condition of the system working within IM / DD is identical (the signal is real and positive) [6].

OFDM converts a frequency-selective channel into a set of parallel frequency-flat channels. Provided the cyclic-prefix (CP) is longer than the maximum delay introduced by the channel, the data at each sub-carrier can be equalized independently using a simple one-tap equalizer [7]. However, the
insertion of CP will lead to reduced spectral efficiency [8]. To increase spectral efficiency, a specially designed filter bank was used instead of CP using an offset quadrature amplitude modulation / OFDM (OQAM / OFDM) system, which is an appropriate alternative to the OFDM system [9].

The biggest challenge facing the VLC system is the limited bandwidth modulation, thus, the modification of FBMC as the solution to this challenge was modified in [2] and [10] to be compatible with the IM / DD real and positive signal.

The techniques used to obtain the real signal in the FBMC system are complicated as in [2],[9] and [10]. The most prominent technique used was Hermitian Symmetry. FFT/IFFT are two of the major components in the system FBMC; however, the result from Hermitian Symmetry symbols frequency was double for the size of the components IFFT / FFT and frequency modulation codes N needed to 2N-point IFFT / FFT [9]. This shows that large size require high precision FFT and thus consume more energy and take up more space in the chip. This causes the greatest complexity.

This paper, to the best of our knowledge, is the first time FBMC modulation will be modified by generating a real signal without using Hermitian symmetry or any complicated technique. This method depends on generating a regular complex FBMC signal and juxtaposing the real and imaginary parts in the time domain to achieve a real FBMC signal. Resulting from this, only N-point IFFT/FFT transforms are demanded to generate a 2N-point real-time OFDM signal.

2. DC-OFDM in VLC

The block diagram in figure 1 on the DCO-OFDM within the VLC system shows where the input data stream was using QAM technology, followed by IFFT using sub-band carrier N to convert the signal from the frequency domain to time domain.

The IFFT algorithm outputs the discrete OFDM symbol vector \( x \) in the time-domain

\[
x_m = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi km}{N}} \quad \text{for} \ 0 \leq m \leq N - 1
\]  

(1)

where \( N \) is the size of IFFT and \( X_k \) is the \( k_{th} \) subcarrier symbol in the frequency domain.

The output signal in (1) is complex (meaning \( a+jb \) \( a \) is real and \( jb \) is the imaginary) which means that it is incompatible with IM / DD based on VLC. Hermitian Symmetry is used to be the IFFT signal to be real and IM / DD compliant (figure 2 illustrates the imaginary signal after the complex signal is inserted through the Hermitian Symmetry). This is a transpose-conjugate copy of the active subcarriers, which is added to the other half of the IFFT frame (acts as a mirror). New elements of the IFFT input vector \( X_H \) are:

\[
X_H = [X_D, X_1, X_2, X_3, \ldots X_{N-1}, X_N, X_N^*, \ldots X_3^*, X_2^*, X_1^*]
\]

(2)

and the DC component, \( X_0 = X_N = 0 \) results in a 2N-point IFFT output of OFDM, therefore, the equation (1) must be modified to

\[
x_m = \frac{1}{N} \sum_{h=0}^{2N-1} X_{H,h} e^{j\frac{2\pi hm}{N}} \quad \text{for} \ 0 \leq m \leq 2N - 1
\]

(3)

where \( h \) is the \( h^{th} \) subcarrier symbol of \( X_H \).

The advantage of OFDM is that it is able to overcome this ISI problem by using the CP listed at the beginning of the OFDM framework. To ensure the unipolar signal meets IM/DD requirements, a DC-offset is added in the DC-coupled optical OFDM (DCO-OFDM) scheme. A DC-offset was implemented in practice as a dc-bias current to drive the LED transmitter. It was added to ensure unipolarity. After it became a real signal and the non-negative being sent was received through the photodetector, the DC-Bias was removed and the CP was also excluded. The signal was converted from
analogue to digital (A / D) and the conversion to recover back to the parallel signal was demodulated using 2N-point FFT, thus restoring the bitstream by performing QAM [11].

Figure 2 illustrates the imaginary signal coming out of IFFT after the Hermitian Symmetry mode where N-point was used and needed to double the number to 2N-point. This in turn increases the complexity of the system and increases power consumption.

![DCO-OFDM Block diagram](image)

**Figure 1.** DCO-OFDM Block diagram

**Figure 2.** Output IFFT imaginary signal after used Hermitian Symmetry.

3. **Conventional DCO-FBMC in VLC**

FBMC has become promising to replace the conventional OFDM in 5G technology which has contributed to improve spectral efficiency because it uses CP and overcomes all the weaknesses of OFDM modulation or any other modulation technique [12]. To make FBMC within a VLC system, it must be IM/DD compliant, i.e. the signal is real and positive. To ensure this, the conventional Hermitian Symmetry method was used to obtain a real signal as shown in figure 3, which shows the main structure of DCO-FBMC.

In equation 4, the signal format is shown for the traditional FBMC system where the signal is complex. Therefore, traditional methods must be used to obtain a real signal from this system.

\[
x(n) = \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} a_{m,n} g_{m,n}(t)
\]  

(4)
Figure 3. Conventional block diagram DCO-FBMC used Hermitian Symmetry.

Figure 3 illustrates the itinerary signal from entering and processing in the Offset QAM (OQAM), where the signal emerges as a complex signal. To make a real signal, it must pass through the Hermitian Symmetry and after converting the frequency domain to a time domain, the signal from the IFFT will be real but bipolar. Equation 4 should be modified as shown in equation 5 as in DCO-OFDM.

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

(5)

where \( m \) is the time index; and \( n \) is the subcarrier index; \( a_{m,n} \) is the symbol (message) being transmitted; \( N \) is the number of subcarriers; and \( g(t) \) is the synthesis function which maps \( a_{m,n} \) into the signal space; \( g_{m,n}(t) \) is the shifted version in time and frequency as (6).

\[ g_{m,n}(t) = h(n - mT_0)e^{i2\pi n/Nk}\left(n - \frac{L_p - 1}{2}\right)e^{j\phi_{m,n}} \]  

(6)

where, \( \tau_0 \) is the symbol spacing in time; \( L_p \) is the length of the pulse shaping filter \((Lp=K*N)\); \( K \) is the overlapping factor as shown in Table 1, \( h(n) \) is the pulse shaping filter (known as the prototype filter). \( k \) is the subcarrier index.

\[ h(n) = 1 + 2 \sum_{k=1}^{K-1} (-1)^k H_k \cos \left( \frac{2\pi kn}{L_p} \right) \]  

(7)

\( H_k \) is the set of coefficients related to \( K \).

The main factor that defines and distinguishes the performance of the prototype of the candidate FBMC system is an overlapping factor \( K \), where the \( K \) value greatly affects the BER, the filter shape and sidelobe. Figure 4 gives different filter windows because of the changing value of \( K \).

| Table 1. Overlap factor K for FBMC |
|-----------------------------------|
| coefficients | K2 | K3 | K4 | K5 | K6 | K7 | K8 |
| h0          | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| h1          | 0.707107 | 0.911438 | 0.971960 | 0.99184131 | 0.99818572 | 0.99938080 | 0.99932588 |
| h2          | 0.411438 | 0.707107 | 0.86541624 | 0.94838678 | 0.97838560 | 0.98203168 |
| h3          | 0.235147 | 0.50105361 | 0.70710678 | 0.84390076 | 0.89425129 |
| h4          | 0.12747868 | 0.31711593 | 0.53649931 | 0.70710678 |
| h5          | 0.06021021 | 0.20678881 | 0.44756522 |
| h6          | 0.03518546 | 0.18871614 |
| h7          | 0.03671221 |
As a result of the use of Hermitian symmetry and the properties of the Inverse Fast Fourier Transformer (IFFT), the imaginary signal was excluded and the outgoing signal was real as shown in figure 5. The complexity that the Hermitian Symmetry adds to the system was observed because it used twice the value of the IFFT, i.e. $2N$. These are simulated as figure 4 at $N = 128$ and $K = 2$.

**Figure 4.** Time domain function of the proposed filter with different $K$ values.

**Figure 5.** The shape of the signal after passing through IFFT denoted that Hermitian Symmetry was successfully used.

4. **Juxtaposed optical DCO-FBMC**
For the FBMC modulation system to be IM / DD compliant, the signal must be real. It was found that this technique was characterized by complexity because it leads to a doubling of the size of IFFT / FFT. This reason and others motivated the researchers to find a way to perform a real signal without complication and not use the Hermitian Symmetry. Therefore, the modulation of FBMC had to be improved to be within VLC. It was found that this technique was characterized by complexity because they lead to a doubling of the size of IFFT / FFT.

4.1. Design Juxtaposed optical DCO-FBMC transmitter.

Figure 6 illustrates the main structure of the DCO-FBMC enhanced design where it is noted that this design focuses mainly on the time domain. In other words, the signal was after IFFT and passing block parallel to serial transform (P/S). This signal is complex (consisting of a real part and an imaginary part) and is similar to the signal emerging from the conventional FBMC system, which is incompatible with IM / DD because as it is not real. Therefore, the imaginary signal should be converted into a real signal as will be explained below. To get a real signal by separating the complex signal into a real and imaginary signal, then converting the imaginary signal to real, and then juxtaposing the real and imaginary respectively, the process is as shown in figure 6.

![Figure 6. Main structure Juxtaposed real and imaginary DCO-FBMC without using Hermitian Symmetry.](image)

In (4) represents the complex main signal coming out of the conventional FBMC system, hence the improvement on the system as explained above. The complex time signal can be represented exactly in (8), and this method is employed after the P/S block.

\[ x(n) = a(n) + jb(n), \quad n = 1, 2, 3, \ldots, K * (N - 1) \]  

(8)

where \(a\) and \(b\) are the real and imaginary parts of \(x(n)\) respectively. A real signal is generated using the above method in (9).

\[ x_{2KN} = \begin{cases} a(n) & n = 0, \ldots, K(N - 1) \\ b(n - KN) & n = KN, \ldots, 2KN - 1 \end{cases} \]  

(9)

Figure 3 shows the real signal and the imaginary signal after their separation before applying the new technique. After that, the imaginary juxtaposed real signal in the new method is employed as in figure 7, thus, the denoted signal length is \(2KN\).
Figure 7. Separate the complex signal into a real and imaginary signal at $N=256$ and $K=2$.

Figure 8. FBMC Juxtaposed signal at length $2KN$.

The signal shown in figure 8 is real but bipolar, which means that it is incompatible with IM / DD because one of the two conditions is incomplete. To resolve this problem, DC-bias technology was added to convert the bipolar to unipolar, and the second condition achieved a real positive signal which is therefore compatible with the IM / DD.

4.2. Design Juxtaposed optical DCO-FBMC receiver.

The optical signal is received by the photodetector and is converted into an electrical signal, as shown in figure 9, where the first step is to remove the DC-bias effect. Then, the signal is separated into two real and imaginary parts as described in (10).

Figure 9. Design new optical DCO-FBMC receiver
\[
y(n) = \begin{cases} 
a_r(n) = y_{2KN}(n), & n = 0, \ldots, K(N - 1) 
b_r(n) = y_{2KN}(KN + n) & n = 0, \ldots, K(N - 1) 
\end{cases}
\]  \hspace{1cm} (10)

where \( a_r \) and \( b_r \) are respectively the real and imaginary components of received signal \( y(n) \) which then reshaped the complex to pass the signal to the analysis filter bank demodulation as the conventional FBMC system.

5. BER performance

Figure 10 shows the results compared to the simulated bit error rate (BER) technology DCO-OFDM, DCO-FBMC traditional (utilising Hermitian Symmetry), and finally, DCO-FBMC technology which uses the new method as a signal-noise ratio (SNR) in dB. This simulation was done at 1000 different M-QAM codes in AWGN from 16 QAM to 256QAM at \( N = 1024 \). The simulation results were great as the DCO-FBMC performance in both new and traditional methods was better and BER was lower than DCO-OFDM and they are similar at the same time.

![Figure 10. The BER as function of SNR of the conventional (Conv) DCO-FBMC, DCO-OFDM the proposed (new) techniques DCO-FBMC.](image)

6. Complexity and power consumption

Using Hermitian Symmetry in the traditional DCO-FBMC system to get a real signal requires additional carrier and additional complexity. This new method to get the real signal does not require any complexity, is very simple and uncomplicated, and does not occupy a place. The complexity was calculated as shown in figure 11.

\[
A_{anew} = 3N \left( \log_2 \left( \frac{N}{2} \right) - 1 \right) + 8 + 4(NK - N + 1)
\] \hspace{1cm} (11)

\[
A_{acon} = 6N(\log_2(N) - 1) + 8 + 4(NK - N + 1)
\] \hspace{1cm} (12)
Figure 11. Illustrates the differences in complexity between the new method and the conventional method.

Figure 11 above shows that the conventional method is more complex than the new method by 50% and this shows an increase in the size of IFFT / FFT which increases power consumption.

7. Conclusion
The new FBMC modulation is compatible with IM / DD without using Hermitian Symmetry as a conventional system to operate within the VLC system. The new method of this technique relies on the complex signal in the time domain where the real signal is separated from the imaginary signal and then the imaginary signal is converted to the real signal. This method increases spectral efficiency, reduces complexity, and reduces energy consumption, which denotes better performance.

8. References
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