Filtered-OFDM for Visible Light Communications

(Invited Paper)

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***Abstract*—In visible light communications (VLCs), adaptive Orthogonal Frequency Division Multiplexing (OFDM) systems can adjust the transmission parameters according to channel estimation results to improve the system performance. Filtered-OFDM (F-OFDM) is a new flexible and adaptive technology based on OFDM systems and can further improve the system performance. In F-OFDM scheme, the out-of-band emission of OFDM signal is greatly inhibited by using the filter and the guard interval of the two subbands is reduced to save the spectrum resources. In this paper, we creatively apply the F-OFDM technology to visible light OFDM systems and derive the specific signal expression. Simulation results show that as the number of quadrature amplitude modulation (QAM) increases, the bit error rate (BER) performance of the F-OFDM system gets worse. Compared with asymmetrically clipped optical OFDM (ACO-OFDM) and direct current biased OFDM (DCO-OFDM) in VLCs, F-OFDM has better BER performance in 4QAM, 16QAM, and 64QAM schemes.**

***Index Terms*—Filtered-OFDM, Visible Light Communication, QAM, ACO-OFDM, DCO-OFDM.**

I. Introduction

The concept of F-OFDM was re-proposed by Huawei at the Mobile World Congress in 2015 [1]. F-OFDM is a kind of adaptive air interface waveform modulation technique with variable subcarrier bandwidth, which is based on the improved scheme of OFDM [2] [3]. The basic idea of F-OFDM technology is to divide OFDM carrier bandwidth into several subbands with different parameters, and to filter the subbands. The guard band consumption between two subbands can be designed as small as possible [4]. For example, in order to realize the Internet-of-Things (IoT) with low power consumption, the single carrier waveform can be adopted in the selected subband. Smaller subcarrier intervals and longer cyclic prefixes(CPs) can be used to combat multi-path channels. In order to achieve a lower air interface delay, a smaller transmission symbol length can be adopted.

VLC is a kind of wireless access technology which uses white light emitting diode (LED) to transmit data. It is the crystallization of the development of optical communication technology and wireless communication technology [5]. VLC is a powerful complement to radio frequency technology in short distance communications and is becoming more and more concerned. The frequency bandwidth of VLC is wide and unrestricted, and we do not need to apply for the license [6]. Therefore, VLC technology has a great advantage [18]. A VLC system uses light wave as carrier to realize information transmission and uses the baseband signal to modulate the light wave. The common modulation methods include: On and Off Keying (OOK), Pulse Width Modulation (PWM), Pulse Position Modulation (PPM), Discrete Multitone Modulation (DMT), Digital Pulse Internal Modulation (DPIM), OFDM, and so on. Among them, OFDM is a multi-carrier modulation technology, which has advantages of high frequency spectrum utilization and anti-multipath interference [7] [8]. Usually, a baseband OFDM signal is complex and bipolar. But in VLC systems, OFDM signals need to be positive and real. So, they need to be treated as single polarization. The first proposed method of single polarization of the visible OFDM symbol is to add direct current offset (DCO) to the bipolar OFDM symbol, which is DCO-OFDM [9] [10]. In order to avoid clipping noise and nonlinear distortion, ACO-OFDM was proposed in 2006 by Armstrong [11] [12]. In 2011, Fenando et al. presented a new method of optical OFDM single polarization—Flip-OFDM [13]. In 2012, Dobroslav and Haas proposed a new method of single polarization of OFDM—Unipolar OFDM (U-OFDM) [14]. In 2013, Salma and Hossam of Scotland put forward an improved algorithm based on the ACO-OFDM, namely Modified ACO-OFDM (MACO-OFDM) [15]. In the same year, Armstrong put forward asymmetrically clipped DC biased optical OFDM (ADO-OFDM) algorithm [16]. In 2014, Haas et al. proposed a method to reduce the spectrum efficiency loss based on the original U-OFDM algorithm [17].

In this paper, an advanced F-OFDM scheme for VLC is proposed, which has flexible configuration parameters. QAM and additive white gaussian noise (AWGN) channel are used in this scheme. We use filter for each subband and analyze BER performance in different situations. The remainder of this paper is organized as follows. Section II describes the system model including F-OFDM system and signal expression. Section III gives the introduction of subband design and parameters, as well as simulation results. Finally, conclusions are given in Section IV.

II. System model

A complete optical communication system based on white LED contains emission, channel transmission and reception. The original binary bit streams drive the LED after preprocess-

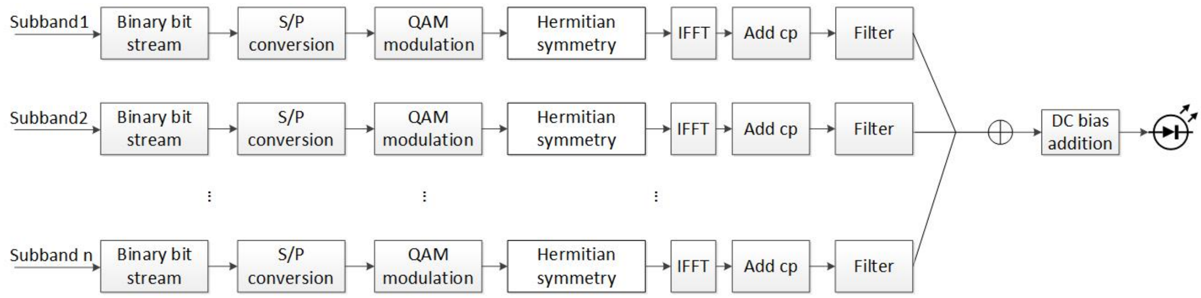


Fig. 1. Transmitter of the VLC F-OFDM system.

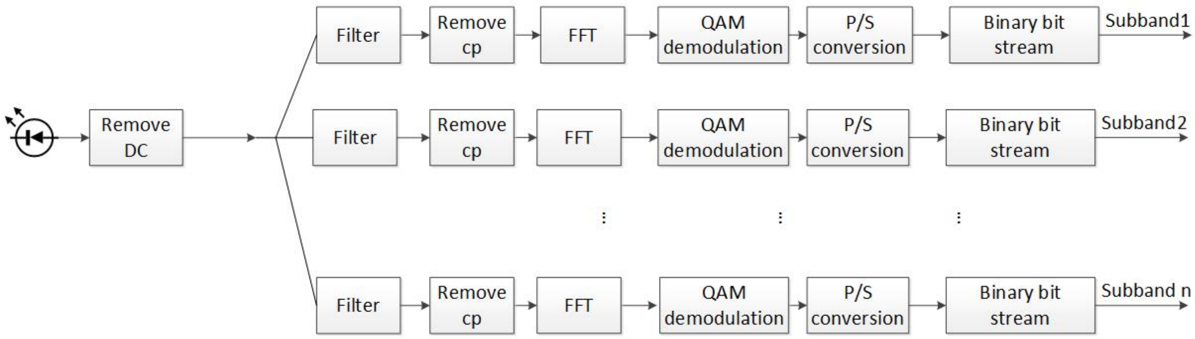


Fig. 2. Receiver of the VLC F-OFDM system.

ing and coding modulation. Next, the system carries out light intensity modulation and converts the electrical signals to light signals. The preprocessing is to compensate the distortion of the signal caused by the device and the channel. By adopting the pre-equalization technique, the response bandwidth of the LED and the transmission rate can be improved. Coding modulation is designed to achieve a higher transmission rate on a limited bandwidth. Due to the limitation of the VLC bandwidth, the transmitter can be designed to use higher order modulation coding techniques to improve the transmission rate of white LED communication system and realise high speed transmission. At present, the most common high order modulation format is QAM-OFDM. In the following subsection, we will introduce the proposed filtered OFDM scheme in detail.

A. Filtered OFDM system

F-OFDM has been a popular modulation scheme in the field of wireless communications in recent years. To apply F-OFDM to VLC system, we should do some changes. The transmitter of VLC F-OFDM system diagram is shown in Fig.1. The F-OFDM system can be divided into several subbands according to the business requirements, and the subband filter is added at transmitter. The basic principle of F-OFDM is that each subband can design adaptive and flexible frame structure. As is known to all, the most important feature of the optical communication system is that it can only transmit positive and real signals. According to the nature of the discrete Fourier transform (DFT), if the input sequence of inverse fast Fourier transform (IFFT) satisfies the hermitian symmetry, the signal obtained after IFFT is the real signal. After that, a single polarization treatment of the bipolar OFDM symbol is needed to convert the bipolar symbol into a positive signal. In addition to that, F-OFDM has the similar processing operations with the OFDM system in respect of modulation, IFFT/FFT, adding CP. The light intensity can not be negative, therefore, a DC bias is added to OFDM signals when we convert the electro signal to optic signal. A bipolar signal can become a single polarity signal, it can be transmitted by light. The receiver is an inverse process of the transmitter shown in Fig.2.

B. Signal expression

The F-OFDM system has multiple subbands, we choose one of these subbands as the representation in the following. The original transmission data is discrete binary bit stream, and the selection criteria of modulation method is preferred to minimize the effect of noise. Here, QAM is used and the orders can be different. IFFT is performed on the modulated signals to turn them into OFDM symbols and N is the IFFT/FFT size. The output signals of IFFT are complex and can not be used in an intensity modulation and direct detection (IM/DD) system based on VLC. To solve this problem, we use hermitian symmetry to get real-valued IFFT output. Let us assume that X_H has a hermitian symmetric structure, i.e.,

$$X_H = (X_0, X_1, ..., X_{N-1}, X_N, {X^*}_{N-1}, ...X_2^*, X_1^*) \quad (1)$$

where X^* is the conjugate of X, X_0=X_N=0, and X_1 to X_{N-1} are complex signals after QAM. The OFDM signals obtained after IFFT are all real numbers. IFFT algorithm can transform a set of multiplexed, overlapping subcarriers in the frequency

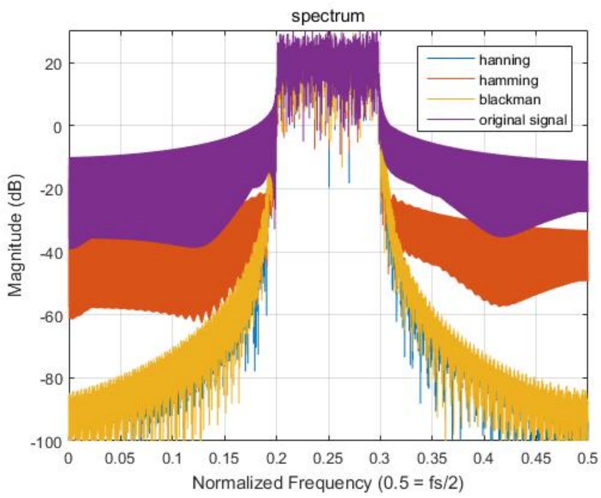


Fig. 3. Signals with different windows.

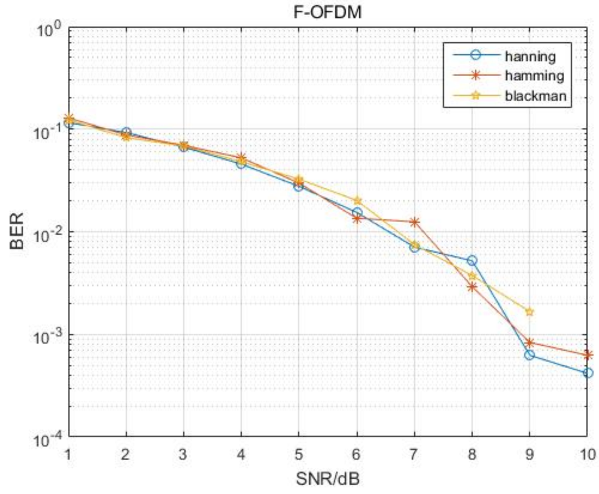


Fig. 4. BER of different windows.

domain into equivalent signals in the time domain. x_n are the time domain signals after IFFT, i.e.,

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j\frac{2\pi kn}{N}}, \qquad n = 0, 1, ..., N-1. \quad (2)$$

where N is the size of IFFT/FFT and X_k is the k^{th} subcarrier symbol. Taking FFT of X_n in (2) gives

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j\frac{2\pi kn}{N}}, \qquad k = 0, 1, ..., N-1. \quad (3)$$

One thing to note is that the input signals of IFFT need to do hermitian symmetry transform shown in (1). The size of results turns to 2N points. So, (2) can be rewritten as

$$x_n = \frac{1}{2N}\sum_{k=0}^{2N-1} X_H e^{j\frac{\pi kn}{N}}, \qquad n = 0, 1, ..., 2N-1. \quad (4)$$

The OFDM symbol is a periodic function with a period $T = 1/\Delta f$, Δf is the subcarrier spacing and can be calculated by $\Delta f = B/(N-1)$, where B is the signal modulation bandwidth.

The F-OFDM signal $\tilde{x}(n)$ is obtained by passing the signal $x(n)$ through the filter $f(n)$ based on window function, which can be represented as

$$w(n) = \begin{cases} 0.5 + 0.5cos(\pi + \pi n)/(\beta N)), & 0 \leq n \leq \beta N \\ 1, & \beta N \leq n \leq N \\ 0.5 - 0.5cos(\pi + \pi n)/(\beta N)), & N \leq n \leq (1+\beta)N \end{cases} \quad (5)$$

where N represents the symbol period before adding the window, and the symbol period after the window changes to (1+ β)N.

C. Subband design

The function of the filter is to have a low out-of-band emission so that the guard interval can be very small between two subbands. The transmission signals of one subband can be represented as

$$\tilde{x}(n) = x(n)w(n). \quad (6)$$

If the number of subband is M, and the signal of each band is expressed by $\tilde{x}(n)$. If the size of $\tilde{x}(n)$ is Q, the transmission signal is a matrix with size of $M \times Q$.

$$s = \sum_{l=1}^{M} \tilde{x}(l) \quad (7)$$

The channel we use is an additive white Gaussian noise (AWGN) channel. So, at the receiver, the received signal is given by

$$y = s + n_A. \quad (8)$$

The algorithm used at the receiver is the inverse process of the transmitter.

III. Results and Discussions

In this section, two parts are presented. The first part is about subband design, it introduces the parameter of the experiment and shows the shape of the signals in different processes. The second part is the simulation analysis, it gives the result of BER of F-OFDM system in different QAM modulation and analyses BER-SNR of three OFDM schemes. In the end, the reasons of different performances are given.

Compared with the transmitter of OFDM, F-OFDM transmitter can be divided into different links with different processing, where different subbands can set different sub-carrier spacing and CP length according to the channel characteristic parameters, the aim is to meet the need of the different business. From Fig.3, we can see that the main difference between F-OFDM and OFDM is out-of-band emission (OOB), F-OFDM is used to control the leakage of the external spectrum by using filter and improve the efficiency of the spectrum. The rest of the F-OFDM is similar to OFDM, and some existing

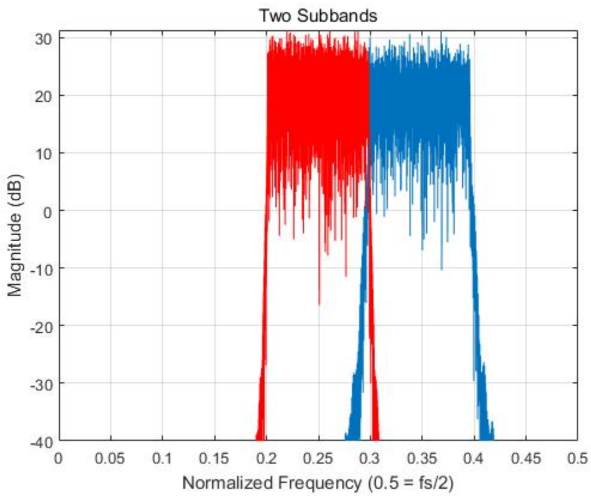


Fig. 5. Signals of two subbands.

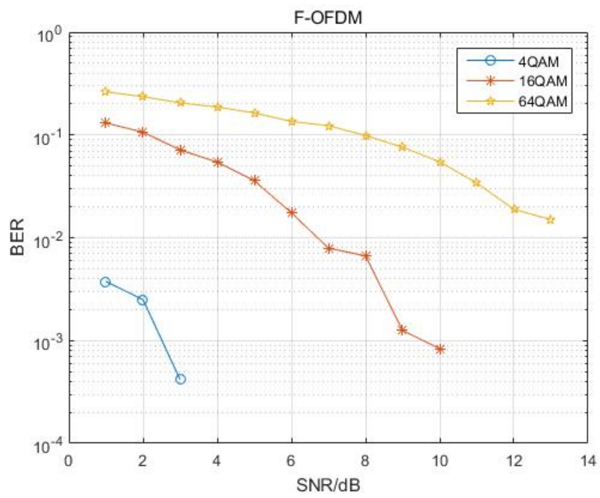


Fig. 6. BER vs. SNR for different QAM schemes in the F-OFDM VLC system.

techniques in OFDM (like MIMO) can be applied directly to F-OFDM to improve system performance.

In the OFDM system, the power spectral density attenuation of out-of-band signal is slow, which means the radiation of out-of-band power is large. Out-of-band radiation can not only cause great pollution to the wireless transmission channel, but also interfere the surrounding equipment. Therefore, the energy of OFDM's side lobe need some methods to attenuate rapidly. Because the frequency of the secondary lobe is very close to the main lobe, the energy of the secondary lobe can not be filtered through a filter. Therefore, the method of filtering the side lobe energy is limited, and adding window is one of the methods. Usually ascending cosine window is used. We choose three representative window function to do the experiments, respectively, hanning window, hamming window, and blackman window. The experimental results are

TABLE I
SIMULATION PARAMETERS.

Parameter	F-OFDM setting
Number of carriers	200/100
IFFT/FFT size	2048/1024
Modulation	4/16/64 QAM
Bandwidth	10 MHz
CP size	1/4 * 2048
Filter	Raised cosine window
Channel	AWGN channel

shown in Fig.3, we can see that compared with hamming window, hanning window and blackman window have more out-of-band attenuation. Fig.4 shows BER curve, there's few difference between three windows. We can choose proper window according to the actual situation.

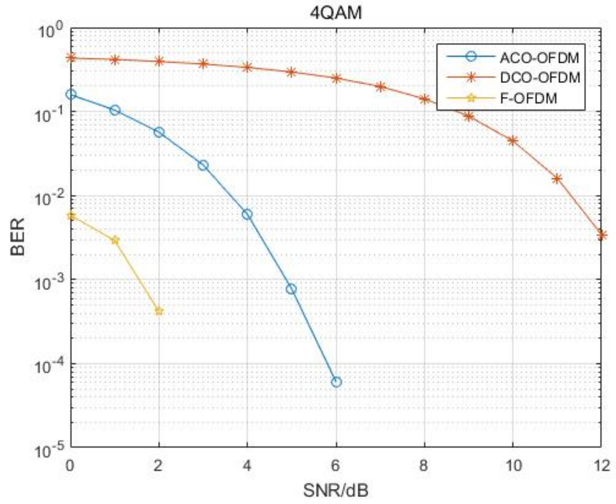
Next, we design two subbands as an example to introduce the F-OFDM system. The parameters are shown in table I.

The designed scheme of two subbands are shown in Fig.5. One of the most important advantage of F-OFDM is that the guard interval can be extremely small with the function of filter. More frequency spectrum can be saved and spectrum utilization will be increased.

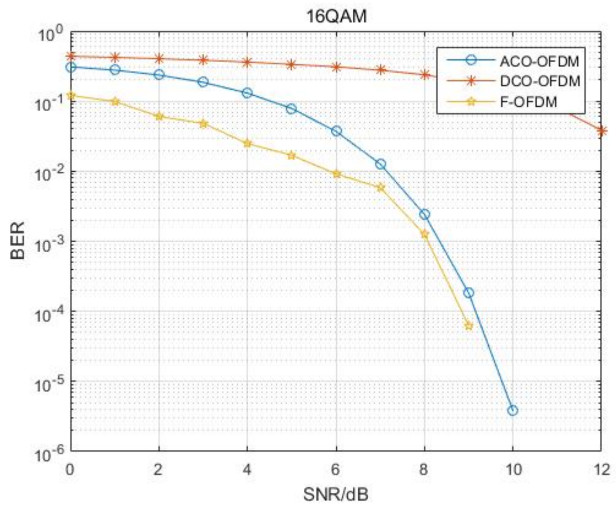
A. Simulation analysis

In order to find the effect of modulation orders on the BER performance, simulations are based on F-OFDM system with different QAM orders as shown in Fig.6. It is obvious that with the increasing of the QAM order, the BER performance becomes worse. when QAM orders become higher, we need a higher signal to noise ratio (SNR) to achieve the same BER.

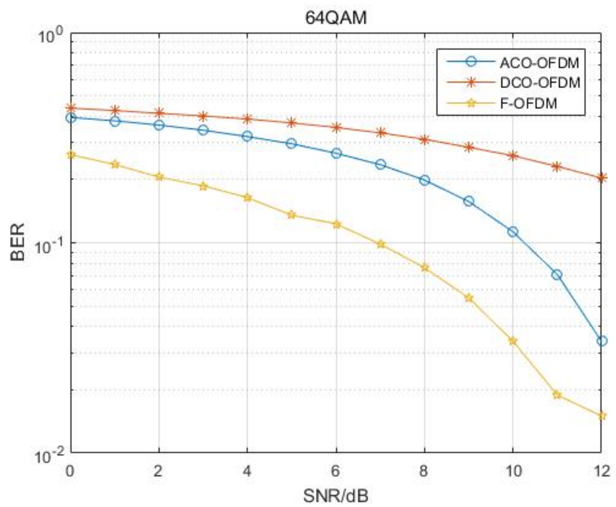
Finally, Fig.7 shows the BER-SNR curve of three OFDM schemes including ACO-OFDM, DCO-OFDM, F-OFDM. From Fig.7 we can see that under the same SNR, the BER of DCO-OFDM is the largest, ACO-OFDM is second, and F-OFDM is the smallest no matter what QAM order is. With the increasing of QAM order, performances of three schemes become more similar. In the same QAM, the performance of the ACO-OFDM system is significantly better than that of DCO-OFDM system. The reason is that DCO-OFDM need add DC before sending signal. At the same time, signal power greatly increases. Under the same SNR, DCO-OFDM system has higher noise power, and the DC bias of the signal must to be reduced in demodulation, so that the receiving SNR of DCO-OFDM system will be smaller than that of ACO-OFDM system, the system error rate will increase. Beyond that, the performance of the F-OFDM system is significantly better than that of ACO-OFDM system, because in the transmission processing, ACO-OFDM symbols lose half of power when they reach the receiver, only half of the power of the polarity OFDM is transmitted. Therefore, ACO-OFDM systems require more SNR than F-OFDM systems to get the same BER.



(a) BER of three OFDM schemes for 4QAM



(b) BER of three OFDM schemes for 16QAM



(c) BER of three OFDM schemes for 64QAM

Fig. 7. BER of three OFDM schemes with (a)4QAM, (b)16QAM, and (c)64QAM.

IV. Conclusions

In this paper, we have proposed a new adaptive F-OFDM scheme for VLC systems. There are some obvious advantages of F-OFDM. First of all, each subband can set different parameters according to demand. Secondly, with suitable filters to suppress the OOB, the guard interval can be reduced to a minimum value. The numerical results have shown that higher order modulation has a worse BER performance. Compared with ACO-OFDM and DCO-OFDM, F-OFDM has a better BER performance.

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