Huffman Coding Based Spatially Modulated Optical MIMO-OFDM

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Abstract

Optical wireless communication (OWC) is a promising new technology for the next generation of wireless communication systems. This paper proposes a generalized index modulation technique based on Huffman coding for multiple input multiple output orthogonal frequency division multiplexing (MIMO-OFDM) OWC systems. With Huffman coding based spatial modulation, the generalization of both conventional spatial modulation and transmit LED selection is possible. The real and imaginary components of the complex time domain OFDM signals are separated first, then the resulting bipolar signals are transmitted over visible light communication channel (VLC) by encoding sign information in LED indices. The proposed scheme achieves considerably better bit error ratio (BER) performance than the existing VLC-MIMO-OFDM. Compared with single- input single-output (SISO) optical OFDM, the spectral efficiency can be doubled by simply exploiting a MIMO configuration.

Keywords — *Optical wireless communication (OWC), Generalised LED index modulation (GLIM), Huffman coding.*

I. INTRODUCTION

Due to increasing demand on wireless applications and services optical wireless communication (OWC) has become an attractive new technology for indoor data transmission as a promising complementary solution to RF systems. The operating range of visible light communication (VLC) is between 400-800nm that could be an optimal solution for indoor mobile communication [1]. The advantages like licence free applications, low cost, high privacy protection, resistance to electromagnetic interference etc. have made VLC a complementary technique to RF communication systems especially for next generation communication systems. Since, intensity modulation direct detection (IM/DD) is widely applied, the conventional OFDM cannot be directly applied in VLC systems. The transmitted signals are constrained to be real valued and non-negative. The direct current (DC) bias addition on bipolar signals make the system power inefficient. This is the main motivation behind the development of New energy and spectrum efficient optical OFDM systems.

VLC systems are still under development and several challenges face these systems, especially in terms of achieving high data rates and using the VLC spectrum efficiently. The main challenges facing high data rate VLC systems are the low modulation bandwidth of the LEDs (typically several megahertz for the blue-chip LED and a few hundred megahertz for the RGB LED) and the inter-symbol interference (ISI) caused by multipath propagation, which limits the data rates in VLC systems. Intensity modulation with direct detection (IM/DD) is typically used in VLC systems because of its simplicity. In IM/DD VLC systems, signals are transmitted through a light emitting diode (LED) in the form of optical power, which means that the modulated signal is non-negative. In the receiver, a photo detector (PD) is employed to convert the optical power signal into electrical signals. A limitation of VLC systems is their limited modulation bandwidth determined by the LED, which is typically in the range of tens of MHz (3-dB bandwidth) only. The equivalent channel for VLC systems is a low-pass channel, which will cause inter-symbol interference (ISI) for high-speed transmission. However, ISI mitigation schemes developed for radio frequency (RF) communications cannot be directly applied to IM/DD VLC systems. Modified orthogonal frequency division multiplexing (OFDM) scheme for VLC systems is briefly explained in section II.

This work aim to develop both spectrum and energy efficient VLC system with improved BER performance. In existing work, without using Hermitian symmetry and DC bias real valued and positive signals can be transmitted using GLIM-OFDM. In this case, only sign information is encoded in the indices of transmitting units. In the proposed work, both sign information and information bits can be encoded in the indices of transmitting units with improved BER performance. Computer simulation result can be obtained using MATLAB.

The rest of this paper is organised as follows. A brief discussion on literature review is presented in section II. In section III, system model is provided. Both computer simulation and theoretical results are provided in section IV and finally, summary and discussions are given in section V.

II. REVIEW OF LITERATURE

There are many studies and works reported related to VC including its importance, applications, opportunities and challenges. It has been reported that there are many modulation techniques used in conventional MIMO-OFDM systems. Since IM/DD technique is used in VLC systems, Hermitian symmetry and DC bias were required to get real and non-negative signals. Most of the conventional OFDM lacks energy and spectrum efficiency. Later many hybrid optical OFDM schemes have been developed by combining some conventional optical OFDM schemes. These hybrid schemes where more spectrally efficient. Recently many optical OFDM schemes has been developed by incorporating MIMO technology, which provides twice the spectral efficiency of SISO systems. Using index modulation techniques in MIMO-OFDM schemes, both Hermitian symmetry and DC bias can be avoided. Some of the important findings and discussions are briefly explained in this section as follows.

The utilization of IM/DD technique in VLC system leads to challenging problems when the goal is to maintain the same spectral and power efficiency. To address these challenges many different methods have been developed. Real time domain signals are directly obtained by applying Hermitian symmetry on Fast Fourier Transform (FFT). But to deal with the bipolar nature of the signals many methods are introduced. One of the straight forward approach to get positive signal is to add a DC bias after inverse FFT (IFFT) operation. The resulting system is known as DC biased optical OFDM (DCO-OFDM) [2]. It is indicated that DCO-OFDM is inefficient in terms of optical power since the DC-bias does not carry information. Another elegant solution to deal with the bipolar nature is asymmetrically clipped optical OFDM (ACO-OFDM) [3]. In ACO-OFDM only the odd sub-carriers are used for modulation. Anti-symmetric wave form could be obtained after IFFT and the negative part is clipped without any information loss. Since DC-bias is not required in ACO-OFDM, which is more energy efficient than DCO-OFDM at the cost of sacrificing half of spectral efficiency. In uni-polar OFDM (U-OFDM) [4] by transmitting positive and negative frames separately the half power penalty in ACO-OFDM caused by time domain clipping can be solved. In U-OFDM, the positive part is transmitted firstly, then the inverted negative part is transmitted. A new method proposed in [5] and [6] offers time domain superposition to achieve the same spectral efficiency as that of DCO-OFDM for both U-OFDM and ACO-OFDM.

Recently, VLC systems with MIMO and spatial modulation (SM) based transmission methods have started to attract significant attention in literature [7]. In index modulation [8] technique the indices of the building blocks are used to transmit additional information bits without using extra energy. Spatial modulation is the most common form of index modulation that can be adopted form VLC-MIMO systems. The performance of SM for indoor VLC is investigated in [9]. To solve the DC bias penalty issue a 2×2 optical SM based structure utilizing two LEDs are introduced in [10]. A novel generalized light emitting diode index modulation based OFDM (GLIM-OFDM) is proposed in [12]. This scheme utilizes LED indices to transmit additional information bits and avoids the typical spectrum efficiency losses incurred by time and frequency domain shaping of OFDM signals. This is achieved by exploiting spatial multiplexing along with LED index modulation. Accordingly, the real and imaginary parts of the complex time domain OFDM signals are separated first, then the resulting bipolar signals are transmitted over a VLC channel by encoding sign information in LED indices. Higher spectral and power efficiencies are achieved by encoding the sign information of complex signals to the location of transmit LEDs. In this scheme, no Hermitian symmetry and DC bias is required to get real and positive signals. Here, no information carrying bits can be encoded in the indices of transmitting units. So, here the next challenge is to develop a new scheme which overcomes this limitation. An adaptive spatial modulation scheme based on Huffman coding that can generalizes both conventional spatial modulation and transmit LED selection is presented in [11]. Utilizing this technology a new optical OFDM scheme can be developed which is discussed in the following section.

III. SYSTEM MODEL

A unified adaptive transmission scheme for MIMO-OFDM system is possible with Huffman mapping. The performance of GLIM-OFDM can be improved by incorporating a probability based spatial modulation using Huffman coding. The main idea of Huffman coding for adaptive spatial modulation is to assign binary codes to spatial symbols (transmit unit index) that take into account the frequency of occurrence of each symbol.

A. Huffman Coding Based Spatial Modulation

The Huffman coding algorithm is an optimal compression algorithm when only the frequency of individual letters are used to compress the data. The idea behind the algorithm is that if you have some letters that are more frequent than others, it makes sense to use fewer bits to encode those letters than to encode the less frequent letters. Recently, research efforts were made to enhance the performance of spatial modulation with channel state information (CSI) under ill-conditioned channels. A heuristic diagonal pre-coder design method for the space shift keying - a simplified spatial modulation can be used to jointly allocates transmit power and optimizes phase rotation. This diagonal pre-coder design is extended to spatial modulation. However, the pre-coder design requires accurate CSI and the algorithm complexity is high. The other dominant transmission scheme for single RF chain MIMO is transmit antenna selection, in which the strongest transmit antenna is selected and all other transmit antennas are kept silent. Different from spatial modulation, the information is carried merely by a signal symbol and no information is conveyed via antenna index. Antenna selection relies on channel feedback to choose the specific antenna, and transmit diversity can be obtained. However, the design flexibility of antenna selection is limited, which restricts its potential to further enhance the system performance. The performance of spatial modulation depends on the channel qualities of N_t links, which makes it inferior when a number of weak links exist. While, the performance of transmit antenna selection only depends on the channel quality of the strongest link, and it is not affected by the weak links. From this, a unified model for spatial modulation and transmit antenna selection based on Huffman coding has been developed.

Huffman coding for adaptive spatial modulation is to assign binary codes to spatial symbols (antenna index) that take into account the frequency of occurrence of each symbol. The antenna information bits are mapped to its corresponding transmit antenna according to the constructed Huffman code. The longer codeword means its corresponding antenna has less chance to be activated and vice versa. In addition, no codeword in the generated codebook should be a prefix of any other codeword. To present the scheme clearly, some examples for N_t = 4 as follows.

TABLE I
Huffman Mapping Scheme for *p* = [1/2; 1/4; 1/8; 1/8]

Bit Sequence	**Spatial Symbol (r)**	**Probability (p)**
0	Tx-1 (e1)	50%
10	Tx-2 (e2)	25%
110	Tx-3 (e3)	12.5%
111	Tx-4 (e4)	12.5%

Example 1: When the probability vector *p*= [1/2; 1/4; 1/8; 1/8], the corresponding Huffman mapping is shown in Table 1. Since no codeword is a prefix of any other codeword, Table 1 is a bijective function between the binary bits and antenna index. The incoming antenna information bits are sequentially detected and then mapped into different transmit antenna indices. If the first bit "0" is detected, then antenna Tx-1 is selected. Otherwise, the first bit is "1", go to detect the second bit. If the second bit "0" is detected, then antenna Tx-2 is selected. Otherwise, the second bit is "1", go to detect the third bit. If the third bit "0" is detected, then antenna Tx-3 is selected. Otherwise, the third bit "1" is detected, then antenna Tx-4 is selected. On the average, the activation probabilities of antennas Tx-1, Tx-2, Tx-3, and Tx-4 are 50%, 25%, 12.5% and 12.5%, respectively. Hence, the transmitted antenna information is up to 1/2 × 1 + 1/4 × 2 + 1/8 × 3 + 1/8 × 3 = 1.75 bits.

Example 2: when the probability vector *p*= [1/4; 1/4; 1/4; 1/4], the transmission scheme is equivalent to the conventional spatial modulation and the corresponding Huffman mapping is shown in Table 2. Information bits carried by antenna index are split into segments with equal length. Thus, the Huffman mapping can map every two bits into the antenna index. Incoming bits "00" mean antenna Tx-1 is activated, "01" for Tx-2, "10" for Tx-3 and "11" for Tx-4. On the average, the activation probabilities of all the antennas should be equal, i.e., 25%. Hence, the transmitted antenna information is up to 1/4 × 2 + 1/4 ×2 + 1/4 × 2 + 1/4 × 2 = 2 bits.

TABLE IIIII
Huffman Mapping Scheme for p = [1/4; 1/4; 1/4; 1/4]

Bit Sequence	**Spatial Symbol (r)**	**Probability (p)**
0	Tx-1 (e1)	50%
10	Tx-2 (e2)	25%
110	Tx-3 (e3)	12.5%
111	Tx-4 (e4)	12.5%

The objective of adaptive spatial modulation is to find p that optimizes the system performance. The design problem can be generalized as follows.

$$\text{P1}=\begin{cases} \max/\min f(p) \\ s{:}t \;\; p \in P \end{cases} \qquad (1)$$

Where *f(p)* is the performance metric, which can be capacity or SER. Due to the binary nature of the Huffman coding scheme, the feasible domain of p is a discrete set which can be represented as

$$\text{P}=\left\{P \setminus \sum_{i=1}^{N_t} p_i = 1,\; p_i \in \{0,1,2^{-1} \ldots 2^{-\beta}\}\right\} \qquad (2)$$

$\beta(0 \le \beta \le N_t)$ is an integer and is related to transmission codebook size. The larger β is, the more transmission schemes are contained in the adaptive transmission and apparently, the better performance will it have. However, larger β brings heavier feedback load for the receiver.

B. Huffman Based GLIM-OFDM

An enhanced version of GLIM-OFDM [12] can be obtained by incorporating an adaptive spatial modulation based on Huffman coding. The block diagram of the Huffman coding based GLIM-OFDM (HGLIM-OFDM) is given in Fig. 1. In this scheme, both sign information and information carrying bits can be transmitted as spatial information. Here, $N\log2(MN_t)$ information carrying bit stream enters the transmitter block, Where *N* is the number of OFDM sub-carriers and *M* is the size of the considered signal constellation such as M-array quadrature phase shift keying (M-QPSK) and N_t is the antenna information bits. In this scheme, the first two bits of the incoming bit stream is used as antenna information bits. So, the

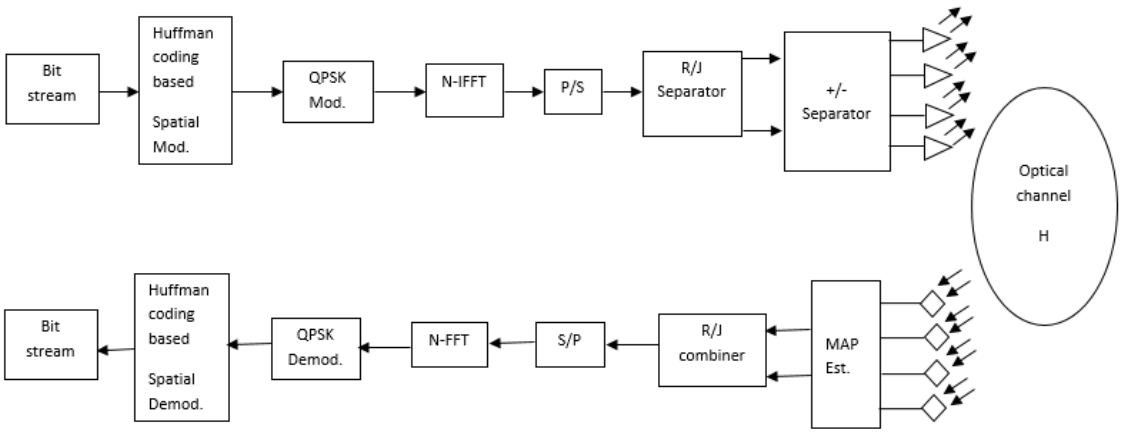

Fig 1: Block diagram of Huffman coding based GLIM-OFDM scheme for a 4×4 MIMO-VLC system

symbols can be grouped as "00", "01", "10" and "11". Hence, the Huffman probability vector is p = [1/4; 1/4; 1/4; 1/4], the transmission scheme is equivalent to the conventional spatial modulation and the corresponding Huffman mapping is shown in Table 2. Incoming bits "00" mean antenna Tx-1 is activated, "01" for Tx-2, "10" for Tx-3 and "11" for Tx-4. On the average, the activation probabilities of all the antennas should be equal, i.e., 25%. This Huffman coding based spatially modulated M-array QPSK symbols are transmitted to the OFDM block. The sign information are encoded in the indices of LEDs.

This enhanced GLIM-OFDM scheme provides better BER performance compared to previously mentioned optical OFDM schemes.

Since SM simultaneously transmits data in the signal domain and the spatial domain, it provides an enhanced spectral efficiency of log2(N_tt) + log2(M) Bits/s/Hz. Hence, from [13] the BER of HGLIM-OFDM becomes

$$BER \geq \frac{2(M-1)}{M N_t \log_2 M N_t} Q\left(\frac{1}{(M-1)}\sqrt{\frac{SNR}{N_t^2}}\right) \quad (3)$$

Where, Q(.) is the complimentary cumulative distribution function, M is the constellation size and N_t is the number transmit antennas. The proposed scheme provides energy efficient communication technique by exploiting the advantage of LED index modulation to avoid Hermitian symmetry and DC bias. From the error performance analysis, it has been concluded that the proposed system yields the best BER performance compared to the existing GLIM-OFDM. The performance analysis and comparison of GLIM-OFDM and HGLIM-OFDM are provided in the next section.

IV. RESULT AND COMPARISON

In this section, the analytical and computer simulation results existing GLIM-OFDM and HGLIM-OFDM schemes are presented. MATAB based program is used for computer simulation.

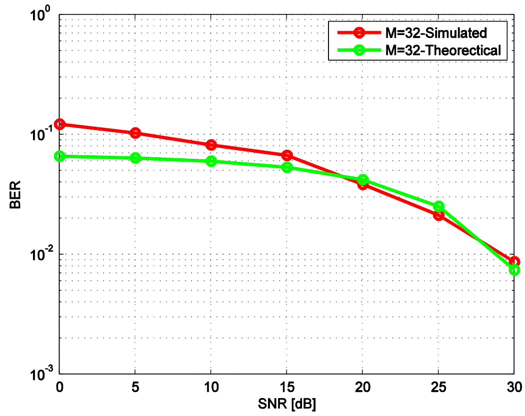

Fig 2: BER Performance of HGLIM-OFDM with M=32

The theoretical as well as computer simulation results of BER performance of GLIM-OFDM with Huffman coding based spatial modulation with $M = 32$ is given in Fig. 2. In simulation, M-array QPSK is used for signal constellation and the number of subcarriers are used as $N = 128$. The theoretical graph is plotted by using the Eqn. 3 given in section 3.

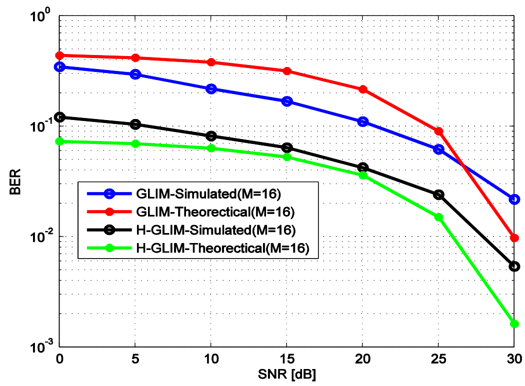

Fig 3: BER Performance Comparison between HGLIM-OFDM and GLIM-OFDM Schemes with M=16

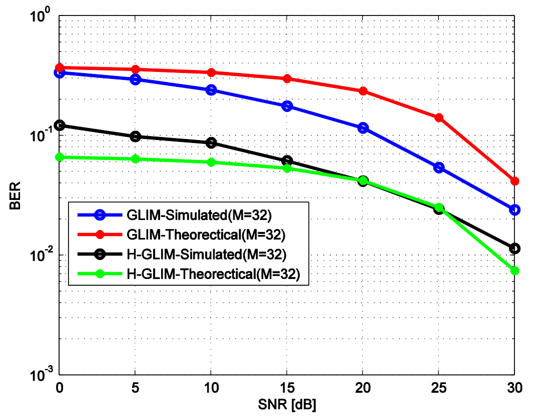

Fig 4: BER Performance Comparison between HGLIM-OFDM and GLIM-OFDM Schemes with M=32

The BER performance comparison of GLIM-OFDM and HGLIM-OFDM for M = 16 is performed in Fig. 3. Similarly, Fig.4 shows the BER performance comparison of GLIM-OFDM and HGLIM-OFDM for M = 32. It is clear that the optical MIMO-OFDM scheme with Huffman coding based spatial modulation provides better error performance compared with existing optical MIMO-OFDM scheme.

V. CONCLUSIONS

VLC technologies, as well as the index modulation concept for MIMO-OFDM systems, such as SM techniques are gaining noticeable attention for the next generation of wireless standards. In this thesis, a Huffman coding based adaptive spatial modulation technique for a 4×4 MIMO system is proposed. This scheme offer twice the spectral efficiency of that of conventional optical OFDM systems by simply exploiting a MIMO configuration. This scheme provides energy efficient communication technique by exploiting the advantage of LED index modulation to avoid Hermitian symmetry and DC bias. From the error performance analysis, it has been concluded that the proposed system yields the best BER performance compared to the existing GLIM-OFDM.

There are still numerous challenges for optical OFDM schemes in VLC systems which have to be addressed in the near future. Firstly, the optical OFDM signals suffer from high peak-to-average power ratio (PAPR), which may cause severe distortions due to the non-linearity of LEDs. Although there have been some PAPR reduction techniques applied to optical OFDM, the resultant PAPR is still higher than the single-carrier VLC systems. Therefore, it is challenging to develop effective PAPR reduction techniques for optical OFDM that can decrease the PAPR sufficiently, whilst ensuring desirable BER performances and high data rates. Besides the energy efficiency of the VLC driver (the LED lamp) is reduced using optical OFDM schemes compared with the switched waveform (SW) based modulations such as on-off keying (OOK). Since high energy efficiency is one of the critical advantages of LED lamps over other traditional lighting devices, optical OFDM schemes with low power consumption at the VLC driver should be developed in order to achieve a balance between the energy efficiency of LED lamps and high data rate.

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