



Performance Analysis of Linear Search MLD for High Rate Full Diversity STBC in PDM-CO-OFDM

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Abstract

This work presents a performance analysis of linear-search high rate full diversity (HRFD) for polarization division multiplexing coherent optical orthogonal frequency division multiplexing (PDM-CO-OFDM) communication systems. The space-time block code (STBC) is used to gain up signal to noise ratio (SNR). To achieve a high rate and full diversity, a STBC code is provided -where it is orthogonal between the consequence times. The maximum likelihood detection (MLD) is used. In addition, the number of searching for decoding is dependent on only constellation sizes while the conventional scheme; ex. the Silver code, its searching grows up exponentially. The proposed method is called high rate full diversity STBC (HRFD-STBC). The system performance of the system is evaluated by numerical simulation method. The results show that the bit error rate (BER) performance of the proposed HRFD-STBC is slightly higher than the Silver Code. However, at the high polarization dependent loss (PDL) channel, the BER of the STBC code is only a little higher than the Silver Code.

Keywords: PDM; CO-OFDM; High Rate Full Diversity; Optical Coherent Communications

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Introduction

Optical orthogonal frequency division multiplexing (O-OFDM) has been investigated for a decade because there are a lot of advantages for optical communication in both direct detection [1] - [2] and coherent detection [3]. However, only coherent detection is considered in this work. It is called coherent optical OFDM (CO-OFDM). CO-OFDM well combat intersymbol interference (ISI), which is caused by polarization-mode dispersion (PMD) and chromatic dispersion (CD), by appending a cyclic prefix (CP) extension. The CP is taken from some last OFDM samples itself. In addition, OFDM has frequency independent loss. This means that each subcarrier is independently attenuated and perhaps only some of the subcarriers are destroyed; whereas, whole carrier will be completely losted in single carrier communication systems. Consequently, by those reasons, CO-OFDM can offer high spectrum efficiency and long communication distances.

Nowadays, polarization division multiplexing (PDM) together with CO-OFDM is very attractive to investigate for gaining up communications speed and capacity. By doing so, the speed and capacity can be double. However, the interference between the transmitted optical light modes will become problem and it reduces signal to noise ratio (SNR). To increase the SNR, in wireless systems, the space-time block code (STBC) [4] is one possible efficient way to employ.

In [5], the authors showed that the Silver code [6] has the best performance for optical communication when compared with the Golden code [7]. In addition, [8] has also found that the system performance of STBC is unchanged when increasing PDL. However, the Silver code superiors the STBC performance code. All the codes, which is previously mentioned, is used to improve the SNR and the maximum likelihood detection (MLD) [9] is generally used to decode the received signal. For the Silver and golden code, they are extremely complex to be decoded. Especially, an exhaustive search will grow up exponentially by the factor of 4. M is constellation size. This would be impossible to implement in the real practical system when M becomes large, such as 64- and 256-quadreture amplitude modulation (QAM). Recently, in [10], other researchers proposed an orthogonal STBC for mode-dependent loss (MDL) mitigation with minimum mean square error (MMSE) channel estimation algorithm. The results proved that by using STBC, the MDL is perfectly solved.

In this work, the low exhaustive search for MLD in PDM-CO-OFDM is proposed. The searching is reduced to be linear and it is dependent on only M . However, the coding rate is moderately reduced and, it can be implemented in hardware. In addition, high rate and full diversity can be achieved, whereas, the conventional STBC, the achieved coding rate is only a half. Additionally, this is the extended work from [12].

Low-Complexity High Rate Full Diversity

In this section, the encoder and decoder for obtaining the high rate and full diversity are discussed. The encoder and decode are detailed in this section.

A. Encoder

To achieve full diversity and high rate, the encoder matrix, which is denoted by C , is given by: [11] - [12]

$$C = \begin{bmatrix} ax_1 + bx_3 / \sqrt{2} & -cx_2^* + dx_3^* / \sqrt{2} \\ ax_2 + bx_3 / \sqrt{2} & ax_1^* + dx_3^* / \sqrt{2} \end{bmatrix}. \quad (1)$$

Where x_1 , x_2 and x_3 are the transmitted arbitrary M-ary QAM symbols. a , b , c and d are the designed parameters for achieving high rate and full diversity, which is generally complex-valued. Next, the encoded data, C is fed into next OFDM modulation, as it will be discussed in the next section. $(\cdot)^*$ stands for conjugate operator.

B. Decoder

At the receiver part, after demodulation by using FFT computation, the received signals in frequency-domain at the x-pol and y-pol for the time t_1 described by:

$$Y_{x-pol,t_1} = H_{1,1}(aX_1 + bX_3 / \sqrt{2}) + H_{1,2}(aX_2 + bX_3 / \sqrt{2}) + Z_1, \quad (2)$$

$$Y_{y-pol,t_1} = H_{2,1}(aX_1 + bX_3 / \sqrt{2}) + H_{2,2}(aX_2 + bX_3 / \sqrt{2}) + Z_2, \quad (3)$$

and at time t_2 can be given by:

$$Y_{x-pol,t_2} = H_{1,1}(-cX_2^* - dX_3^* / \sqrt{2}) + H_{1,2}(cX_1^* + dX_3^* / \sqrt{2}) + Z_3, \quad (4)$$

$$Y_{y-pol,t_2} = H_{2,1}(-cX_2^* - dX_3^* / \sqrt{2}) + H_{2,2}(cX_1^* + dX_3^* / \sqrt{2}) + Z_4, \quad (5)$$

next, to achieve full diversity, the following step of decoding for X_1 and X_2 are derived by:

$$\begin{aligned} Z_1 &= Y_{x-pol,t_1} - bX_3 / \sqrt{2}(H_{1,1} + H_{1,2}) \\ &= a(H_{1,1}X_1 + H_{1,2}X_2) + Z_1, \end{aligned} \quad (6)$$

$$\begin{aligned} Z_2 &= Y_{x-pol,t_2} - dX_3^* / \sqrt{2} (H_{1,2} - H_{1,1}) \\ &= c(H_{1,2}X_1^* - H_{1,1}X_2^*) + Z_2, \end{aligned} \quad (7)$$

$$\begin{aligned} Z_3 &= Y_{y-pol,t_1} - bX_3 / \sqrt{2} (H_{2,1} + H_{2,2}) \\ &= a(H_{2,1}X_1 + H_{2,2}X_2) + Z_3, \end{aligned} \quad (8)$$

$$\begin{aligned} Z_4 &= Y_{y-pol,t_2} - dX_3^* / \sqrt{2} (H_{2,2} - H_{2,1}) \\ &= c(H_{2,2}X_1^* - H_{1,1}X_2^*) + Z_4, \end{aligned} \quad (9)$$

then, multiply those signal by channel matrix, H , we get

$$W_{1,X_1} = H_{1,1}^* Z_1 = a \left(|H_{1,1}|^2 X_1 + H_{1,1}^* H_{1,2} X_2 \right) + H_{1,1}^* Z_1, \quad (10)$$

$$W_{2,X_1} = H_{1,2} Z_2^* = c^* \left(|H_{1,2}|^2 X_1 + H_{1,1}^* H_{1,2} X_2 \right) + H_{1,2} Z_2^*, \quad (11)$$

$$W_{3,X_1} = H_{2,1}^* Z_3 = a \left(|H_{2,1}|^2 X_1 + H_{2,1}^* H_{2,2} X_2 \right) + H_{2,1}^* Z_3^*, \quad (12)$$

$$W_{4,X_1} = H_{2,2} Z_4^* = c^* \left(|H_{2,2}|^2 X_1 + H_{2,1}^* H_{2,2} X_2 \right) + H_{2,2} Z_4^*. \quad (13)$$

Finally, the estimated signal of X_1 , which is denoted by \tilde{X}_1 , becomes:

$$\begin{aligned} \tilde{X}_1 &= (W_{1,X_1} + W_{3,X_1}) / a + (W_{2,X_1} + W_{4,X_1}) / c^* \\ &= \left(|H_{1,1}|^2 + |H_{1,2}|^2 + |H_{2,1}|^2 + |H_{2,2}|^2 \right) X_1 + \eta_1, \end{aligned} \quad (14)$$

where $\eta_1 = (H_{1,1}^* Z_1 + H_{2,1}^* Z_3) / a + (H_{1,2} Z_2^* + H_{2,2} Z_4^*) / c^*$; and by computing $W_{1,X_2} = H_{1,2}^* Z_1$, $W_{2,X_2} = H_{1,1} Z_2^*$, $W_{3,X_2} = H_{2,2}^* Z_3$ and $W_{4,X_2} = H_{2,1} Z_4^*$, the estimated signal of X_2 , which is denoted by \tilde{X}_2 , becomes:

$$\begin{aligned} \tilde{X}_2 &= (W_{2,X_2} + W_{4,X_2}) / a - (W_{1,X_2} + W_{3,X_2}) / c^* \\ &= \left(|H_{1,1}|^2 + |H_{1,2}|^2 + |H_{2,1}|^2 + |H_{2,2}|^2 \right) X_2 + \eta_2, \end{aligned} \quad (15)$$

where $\eta_2 = (H_{1,2}^* Z_1 + H_{2,2}^* Z_3) / a + (H_{1,1} Z_2^* + H_{2,1} Z_4^*) / c^*$.

As can be seen, we need to find only X_3 to obtain \tilde{X}_1 and \tilde{X}_2 . In this work, an exhaustive search or maximum likelihood detection (MLD) is used which X_3 minimizes the Euclidean distance metric:

$$\tilde{X}_3 = \arg \min_i \left\{ D_i(\tilde{X}_{1,i}, \tilde{X}_{2,i}, X_{3,i}) \right\}, \quad (16)$$

where

$$D_i(\tilde{X}_{1,i}, \tilde{X}_{2,i}, X_{3,i}) = \left\{ \begin{aligned} & \left| Y_{x-pol,t_1} - H_{1,1}(a\tilde{X}_{1,i} + bX_{3,i}/\sqrt{2}) + H_{1,2}(a\tilde{X}_{2,i} + bX_{3,i}/\sqrt{2}) \right| + \\ & \left| Y_{x-pol,t_2} - H_{1,1}(-c\tilde{X}_{2,i}^* - dX_{3,i}^*/\sqrt{2}) + H_{1,2}(c\tilde{X}_{1,i}^* + dX_{3,i}^*/\sqrt{2}) \right| + \\ & \left| Y_{y-pol,t_1} - H_{2,1}(a\tilde{X}_{1,i} + bX_{3,i}/\sqrt{2}) + H_{2,2}(a\tilde{X}_{2,i} + bX_{3,i}/\sqrt{2}) \right| + \\ & \left| Y_{y-pol,t_2} - H_{2,1}(-c\tilde{X}_{2,i}^* - dX_{3,i}^*/\sqrt{2}) + H_{2,2}(c\tilde{X}_{1,i}^* + dX_{3,i}^*/\sqrt{2}) \right| \end{aligned} \right\} \quad (17)$$

where $i = 1 \dots M$ is QAM look-up table (LUT) indices and the size of the LUT is equal to M .

From now, we get all \tilde{X}_1 , \tilde{X}_2 and \tilde{X}_3 . It is showed that the complexity increasing is dependent on M-ary QAM size of X_3 and full diversity can be obtained. Obviously, the searching for X_3 is depepent only on M while the conventional ML method needs M^4 . Consequently, this is linear search for D . For example, if we use $M = 64$. The searching of the conventional one is $64^4 = 16,777,216$. This is impossible to implement in hardware.

System Consideration

In this section, the system used for low-complex high rate and full diversity PDM-CO-OFDM is detailed. It is shortly called HRFD-STBC. The system diagram is depicted in Figure 1.

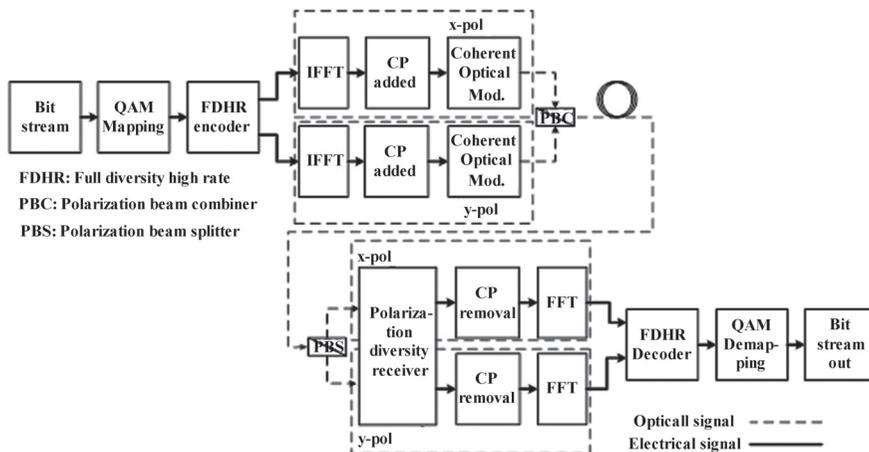


Figure 1 PDM-CO-OFDM diagram for low-complex high rate full diversity communication systems

At the transmitter part, the bit streaming is fed to M-ary QAM mapping unit to obtain a symbol where it is a set of the number of bits. For instance, 16-QAM symbol uses four bits in one set. Next, the QAM symbol is sent to the HRFD-STBC encoder to prepare the code word. The encoder constrains two outputs which are x-pol and the other is y-pol. After that, both x-pol and y-pol signals are fed into Invert Fast Furrier Transforms (IFFT) to convert that signal to time-domain signal. Then, to neglect the dispersive optical channels such as CD and PMD, a cyclic prefix (CP) is added to the head of each OFDM. Then, both electrical signal of x-pol and y-pol OFDM symbol in time-domain is fed into optical modulator where dual Mach-Zehnder modulator is used. Finally, an optical polarization beam combiner (PBC) is used to combine the optical light signal and transmit it out to optical fiber.

At the receiver part, the received optical signal is first spitted into two orthogonal parts, which are x-pol and y-pol, by using optical polarization beam splitter (PBS). The two parts are fed into polarization diversity optical demodulator separately. Next, each of that is converted to electrical signal and the CP is removed in the following. After that, the useful sample is converted to frequency-domain by using FFT. Then, the FFT computation output is fed into HRFD decoder which is used to decode the information data as explained in the last section. Finally, the decoded QAM demapping is used to map the decoded QAM symbol to be bits out stream in the last process.

Table 1 Simulation parameters

Parameters	Quantity
Sampling rate	32 Gs/s
Effective bits efficiency	12
Mean DGD	$0.1 ps / \sqrt{km}$
IFFT/FFT size	1024
Oversampling factor	1/2
CP length factor	128 (= 1024/8)
Fiber length	1,000 km

The optical channel consideration impairments in this work are the PMD and PDL. The two optical channels, H , impacts can be expressed by:

$$H(k) = H_{PMD}(k)H_{PDL}, \quad (18)$$

where k denotes the frequency index. H_{PMD} and H_{PDL} are PDM and PDL, respectively. Both are obtained by a concatenation of many elements. Each element of $H_{PMD}(k)$ is denoted by the following equation [8], [13]:

$$H_{PMD}(k) = R\zeta(k)R^{-1}, \quad (19)$$

where R is rotation matrix which can be expressed by:

$$R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}. \quad (20)$$

In equation (5), θ is the reference angle between the polarizations and the principle state of polarization (PSP). PMD is denoted by $\zeta(k)$ and expressed as:

$$\zeta(k) = \begin{bmatrix} e^{(jk\tau/2)} & 0 \\ 0 & e^{(-jk\tau/2)} \end{bmatrix}, \quad (21)$$

where τ is differential group delay (DGC).

PDL is assumed to be wavelength independent and given by the following equation.

$$H_{PDL} = R\psi R^{-1}, \quad (22)$$

where ψ represents PDL and given by :

$$\psi = \begin{bmatrix} \sqrt{1-\gamma} & 0 \\ 0 & \sqrt{1+\gamma} \end{bmatrix}. \quad (23)$$

γ is attenuation parameter and it generally relates to a standard deviation of a zero-mean Gaussian distribution which is defined in [8], $\Gamma_{dB} = 10 \log_{10}((1-\gamma)/(1+\gamma))$.

From the expression above, the PMD generates frequency dependent loss (or attenuate) which destroys each subcarrier of each OFDM separately and/or some subcarriers are not effects as shown in [3]. The PDL attenuates the optical power in some modes. Therefore, the noise would be gained up at the receivers.

Simulation Results

The detail of system performance of HRFD-STBC for PDM CO-OFDM is studied in this section. The parameters used in this work are shown in Table 1. To achieve full diversity

and high rate for the transmitted power of any QAM size, the designed parameters of $a = c = 1/\sqrt{2}$, $d = e^{-i\pi/2}b$ and $b = \left[(1-\sqrt{7}) + i(1+\sqrt{7}) \right] / (4\sqrt{2})$ [10] are used. Two important issues are investigated. Firstly, the system performance comparison of the proposed method with the existing Silver Code (SC), Golden Code (GC) and conventional STBC (CSTBC) are considered.

Figure 2 shows the bit error rate (BER) performance comparisons between those schemes under PMD and PDL environments where the DGC is 3.16 ps ($= 0.1 \cdot \sqrt{1,000}$). Optical signal to noise ratio (OSNR) is varied from 0 to 25 dB. The PDL of 4 dB is assumed. The SC and GC are decoded by MLD while HR-STBC uses the decoding step from the previous section; and the conventional STBC uses the method in [4]. To get the same bit efficiency per time slot of coding, the SC and the GC employs 8-QAM, CSTBC uses 64-QAM and HR-STBC uses 16-QAM. As can be seen the SC outperforms GC and STBC. However, at the high OSNR (more than 15 dB in Figure 2), HR-STBC has the same BER as SC. More importantly, HR-STBC gives lower computation complexity. For SC and GC, the requirement of exhaustive search is 4096 ($= 84$) while the HR-STBC is only 16. In addition, STBC gives the worse BER performance.

Secondly, the system performance under PDL is investigated. Figure 3 plots the BER versus OSNR where the PDL is varied from 2 to 6 dB and the DGC is the same as Figure 2 16-QAM is used. The BER of the SC code slightly increased when the PDL increased. At 6 dB of PDL, the BER for the SC is only a bit higher than that PDL of 2 dB. However, HR-STBC gives the same BER for all PDL. This means that HR-STBC exhibit likes STBC; but, HR-STBC achieves higher rate and full diversity.

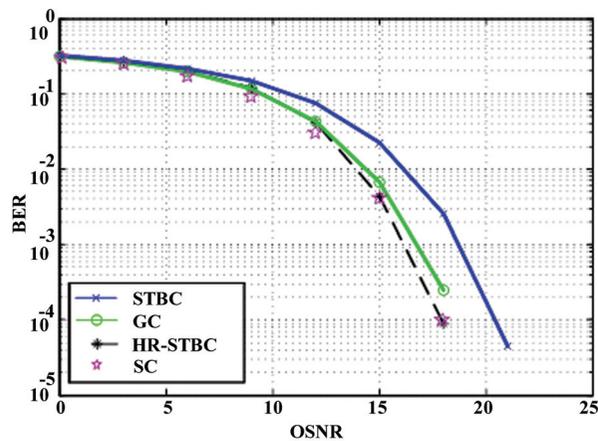


Figure 2 BER versus OSNR for the system performance comparison of the HR-STBC with SC, GD and STBC.

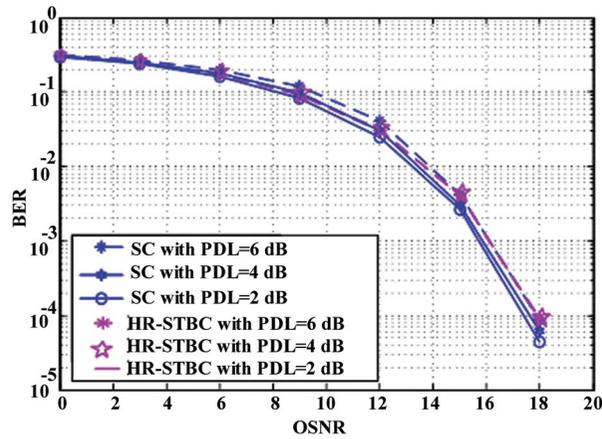


Figure 3 Performance comparison of PDL tolerance of the HR-STBC and SC.

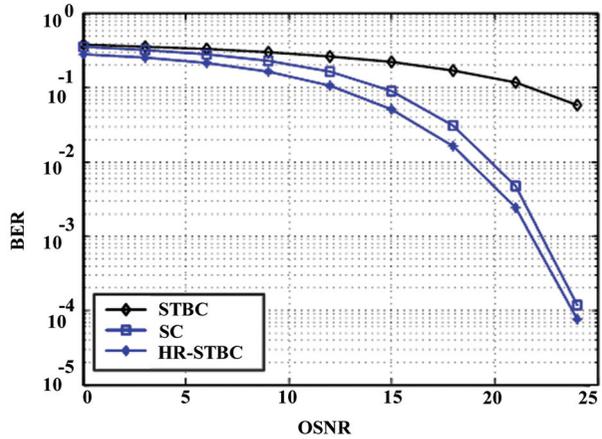


Figure 4 High spectrum efficiency of PDL 6 dB for the HR-STBC and SC.

Figure 4 plots a 20 bits spectrum efficiency of PDL = 6 dB for the HR-STBC and SC. In this case, STBC used 1024-QAM while HR-STBC uses 64-QAM for x_1 and x_2 and 16-QAM for x_3 and x_4 , respectively. As can be seen, the HR-STBC outperforms conventional STBC. Especially, it also gives better BER than SC. Therefore, from all the results, we can conclude on the proposed method superior for both BER performance and low complexity.

Conclusion

The low-complex and high rate full diversity had been proposed and analyzed. It is called high rate space-time block code (HR-STBC). We have compared the HR-STBC performance

with SC, GC and CSTBC code. The linear impacts of optical channel, which are PMD and PDL, are taking into account. The proposed HR-STBC has much lower complexity when it is compared with SC and GC; but, the system performance is only slightly lower than those codes. More importantly, the BER performance of the proposed method is only slightly higher than SC method. The complexity is reduced to only the constellation size. Therefore, this would be the key to implementation in hardware for high speed optical communication in the future.

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