High-Order Intensity Modulations for OSTBC in Free-Space Optical MIMO Communications

Ren Tian-Peng, Chau Yuen, Yong Liang Guan, and Tang Ge-Shi

***Abstract*—Recently, Simon-Vilnrotter and Premaratne-Zheng modified the binary pulse-position modulation (PPM) to support free-space optical (FSO) multi-input multi-output (MIMO) systems with orthogonal space-time block coding (OSTBC) that requires the use of negative symbols. In this paper, we extend the investigation to optical OSTBC schemes with high-order intensity modulation. A necessary and sufficient condition for the high-order intensity modulation to maintain the orthogonality of the applied OSTBC is derived, and four Q-ary intensity modulation schemes satisfying this condition are proposed. In asynchronous FSO MIMO channels in which the signals from different transmitters arrive at the receiver with timing misalignment, the proposed modulation schemes can be used with shift-OSTBC to mitigate inter-symbol interference (ISI) and provide diversity gain.**

***Index Terms*—Free space optical MIMO, higher order intensity modulation.**

I. Introduction

FOR applications where line-of-sight (LOS) is available between transmitter and receiver, free-space optical (FSO) communications offer bandwidth advantage over conventional microwave technology [1] [2] [3]. However, due to channel effects such as dust, rain, fog and atmosphere turbulence, severe reception error or communication interruption may occur. An effective method to enhance the reliability of communication link is to provide redundancy for the receiving signal, hence the orthogonal space-time block codes (OSTBC) with symbolwise maximum-likelihood (ML) linear decoding, extensively studied in RF communications [4] [5], is becoming an active research topic in FSO multi-input multi-output (MIMO) systems [6] [7].

In FSO MIMO systems employing direct detection at the receiver, intensity modulation with unipolar signals is commonly used to convey the information. Different from RF wireless applications, intensity modulation cannot be applied directly with OSTBC because OSTBC requires the negation of optical signals, which is not possible for intensity modulation. Hence, binary pulse position modulation (PPM) has been modified for use with OSTBC in FSO MIMO systems in [6] [7]. Although repetition coding is also able to provide diversity gain to FSO communications [8], it fails when the signals from different transmitters arrive at the receiver with timing misalignment. This may occur when the transmitter synchronization is not done well, or when the signal propagation times from different transmitters to the receiver differ by more than 1 time slot. On the other hand, there exist OSTBC which can provide diversity gain even in asynchronous FSO MIMO channels. Such asynchronous OSTBC, such as the "shift-OSTBC"in [9], is typically used in conjunction with high-order modulation. To use shift-OSTBC in FSO MIMO systems, negation of high-order modulation symbols is again necessary. In this paper, Q-ary intensity modulation schemes that support synchronous and asynchronous OSTBC of arbitrary dimension for FSO MIMO communications are investigated. The intensity modulation schemes considered include constant-amplitude PPM and pulse-width modulation (PWM), as well as multi-amplitude amplitude-shift keying (ASK). The OSTBC considered supports two or more optical lasers (transmitters) and photodetectors (PD, receivers).

In what follows, bold upper case and lower case letters denote matrices and vectors, respectively; $\mathbf{X}^T$ and $\mathbf{X}_{ij}$ denote the transpose and the i-th row, j-th column element of a matrix $\mathbf{X}$; $\widehat{s}$ represents the estimation of a symbol s; $g^{-1}(\cdot)$ denotes the inverse of a function $g(\cdot)$.

II. OSTBC with Intensity Modulation

In FSO MIMO systems, we employ N separate optical lasers, assumed to be intensity-modulated only, together with K PD, assumed to be ideal noncoherent (direct-detection).

A system diagram is shown in Fig. 1, where an $M \times N$ OSTBC matrix (with orthogonality) $\mathbf{X}(s_1, \cdots, s_L) \triangleq \mathbf{X}(s_l)$ over M time slots [4] [5] is applied and non-negative s_l $(l = 1, \cdots, L)$ are intensity modulated symbols. Let $\mathbf{H} = [\mathbf{h}, \mathbf{h}_2 \cdots, \mathbf{h}_K]^T = [h_1, h_2, \cdots, h_N; \cdots; h_{(K-1)N+1}, h_{(K-1)N+2}, \cdots, h_{KN}]^T$ be the channel coefficient matrix whose elements h_{kn} $(k = 1, \cdots, K,\ n = 1, \cdots, N)$ denote the quasi-static channel coefficients between the n-th laser source and the k-th PD receiver, $\mathbf{R} = [\mathbf{r}, \mathbf{r}_2 \cdots, \mathbf{r}_K]^T = [r_1, r_2, \cdots, r_M; \cdots; r_{(K-1)M+1}, r_{(K-1)M+2}, \cdots, r_{KM}]^T$ denote the received signal matrix where $r_{(k-1)M+t}$ $(t = 1, 2, \cdots, M)$ is the signal received on the k-th PD receiver at time t, we have the transmit-receive signal relationship as:

$$\mathbf{R} = \sqrt{\rho}\mathbf{X}(s_l)\mathbf{H} + \mathbf{Z} \tag{1}$$

where $\mathbf{Z} = [\mathbf{z}, \mathbf{z}_2 \cdots, \mathbf{z}_K]^T = [z_1, z_2, \cdots, z_M; \cdots; z_{(K-1)M+1}, z_{(K-1)M+2}, \cdots, z_{KM}]^T$ is an additive white Gaussian noise (AWGN) matrix, ρ is the average signal-to-noise ratio (SNR) at the PD receivers.

Manuscript received May 18, 2013. The associate editor coordinating the review of this letter and approving it for publication was G. Colavolpe.

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Digital Object Identifier 10.1109/WCL.2013.081513.130360

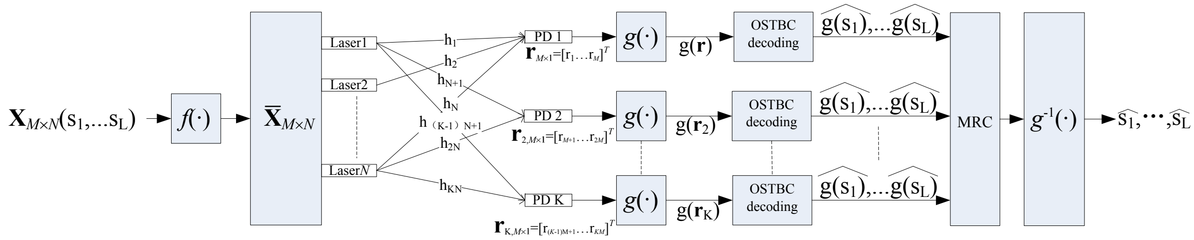

Fig. 1. Block diagram of an FSO OSTBC system with high order intensity modulation.

In most, if not all, OSTBC, certain signals in the codeword must be negated to achieve the orthogonality [5]. To apply non-negative intensity modulated symbols s_l to OSTBC, we introduce a modulation mapping function $f(s_l)$ in the OSTBC matrix $\mathbf{X}$ to obtain a modified version $\bar{\mathbf{X}}$ as shown in (2).

$$\bar{\mathbf{X}}_{ij} = \begin{cases} -\mathbf{X}_{ij}(f(s_l)), & \text{if } \mathrm{sign}(\mathbf{X}_{ij}) \text{ is negative;} \\ \mathbf{X}_{ij}(s_l), & \text{otherwise.} \end{cases} \tag{2}$$

Then all $\mathrm{sign}(\bar{\mathbf{X}}_{ij})$ are non-negative to qualify for the FSO intensity modulation communications. However, $\bar{\mathbf{X}}$ may not be orthogonal. To achieve orthogonal decoding, a linear *post-receiving* function $g(\cdot)$ with the following properties should be introduced in the receiver before OSTBC decoding:

$$g(s) \not\equiv 0 \qquad \text{(otherwise the information will be lost)} \tag{3a}$$

$$g(Cs) = C \cdot g(s) \qquad (C \text{ is a constant value}) \tag{3b}$$

$$g(s_1 + s_2) = g(s_1) + g(s_2) \tag{3c}$$

In the following, we denote that $(g(\mathbf{X}))_{ij} \triangleq g(\mathbf{X}_{ij})$.

A. 2×2 Alamouti Code

For example, consider Alamouti code $\mathbf{X}_{\text{Ala}} = \left[\begin{smallmatrix} s_1 & s_2 \\ s_2 & -s_1 \end{smallmatrix}\right]$ in [4], the modified Alamouti code given by (2) will be $\bar{\mathbf{X}}_{\text{Ala}} = \left[\begin{smallmatrix} s_1 & s_2 \\ s_2 & f(s_1) \end{smallmatrix}\right]$, where both s_i and $f(s_i)$ $(i = 1, 2)$ are non-negative intensity modulated. Substituting $\bar{\mathbf{X}}_{\text{Ala}}$ into (1), the received signal matrix at the first PD receiver can be obtained as:

$$\mathbf{r} = \sqrt{\rho}\bar{\mathbf{X}}_{\text{Ala}}\mathbf{h} + \mathbf{z} = \sqrt{\rho}\begin{bmatrix} s_1 h_1 + s_2 h_2 \\ s_2 h_1 + f(s_1) h_2 \end{bmatrix} + \mathbf{z} \tag{4}$$

Using the post-receiving function $g(\cdot)$ on $\mathbf{r}$ in (4) at the receiver, we have:

$$\begin{aligned} g(\mathbf{r}) &= \sqrt{\rho} g(\bar{\mathbf{X}}_{\text{Ala}})\mathbf{h} + g(\mathbf{z}) \\ &= \sqrt{\rho}\begin{bmatrix} g(s_1)h_1 + g(s_2)h_2 \\ g(s_2)h_1 + g(f(s_1))h_2 \end{bmatrix} + g(\mathbf{z}) \end{aligned} \tag{5}$$

Note that $g(\mathbf{z})$ is still an AWGN vector since $g(\cdot)$ is linear.

Following [4] to left multiply a unitary matrix $\left[\begin{smallmatrix} h_1 & -h_2 \\ h_2 & h_1 \end{smallmatrix}\right]$ on $g(\mathbf{r})$ in (5), we can obtain

$$\begin{aligned} & g(s_1)h_1^2 - g(f(s_1))h_2^2 \\ & = \frac{1}{\sqrt{\rho}}((g(r_1)h_1 - g(r_2)h_2) - (g(z_1)h_1 - g(z_2)h_2)) \end{aligned} \tag{6a}$$

$$\begin{aligned} & g(s_2)(h_1^2 + h_2^2) + (g(s_1) + g(f(s_1)))h_1 h_2 \\ & = \frac{1}{\sqrt{\rho}}((g(r_1)h_2 + g(r_2)h_1) - (g(z_1)h_2 + g(z_2)h_1)) \end{aligned} \tag{6b}$$

Now, view $g(s_l)$ as the "transformed" information symbols for detection. To achieve symbolwise ML linear decoding of $g(s_l)$, $l = 1, 2$, $g(\cdot)$ needs to be designed to satisfy the following conditions:

$$g(f(s_l)) \equiv C_1 g(s_l) + C_2 \qquad \leftarrow \text{from (6a)} \tag{7a}$$

$$g(s_l) + g(f(s_l)) \equiv C \qquad \leftarrow \text{from (6b)} \tag{7b}$$

where C_1, C_2 and C are constant. Substituting (7a) into (7b), we have

$$(1 + C_1)g(s_l) \equiv C - C_2 \tag{8}$$

Since s_l and $g(s_l)$ are random, it is easy to see that only $C_1 = -1$ and $C_2 = C$ can guarantee (8), i.e., the former is a necessary and sufficient condition for the latter. Substituting $C_1 = -1$ and $C_2 = C$ to (7), the necessary and sufficient condition for $g(\cdot)$ to achieve symbolwise ML linear decoding of the Alamouti code can be rewritten as

$$g(f(s_l)) = -g(s_l) + C \tag{9}$$

where the constant value C will depend on the functions $f(\cdot)$ and $g(\cdot)$ selected, and will be illustrated later in Section III.

Finally, substitute (9) into (6), OSTBC decoding of $g(s_l)$ is:

$$\widehat{g(s_1)} = \frac{1}{\sqrt{\rho}} \frac{g(r_1)h_1 - (g(r_2) - \sqrt{\rho}Ch_2)h_2}{h_1^2 + h_2^2},$$

$$\widehat{g(s_2)} = \frac{1}{\sqrt{\rho}} \frac{g(r_1)h_2 + (g(r_2) - \sqrt{\rho}Ch_2)h_1}{h_1^2 + h_2^2}.$$

Using the maximal ratio combining (MRC) [10] for K PD receivers, the information symbols can be obtained as:

$$\widehat{g(s_1)} = \frac{1}{\sqrt{\rho}} \frac{\sum\limits_{k=1,3,\cdots K} g(r_k)h_k - \sum\limits_{k=2,4,\cdots K}(g(r_k) - \sqrt{\rho}Ch_k)h_k}{\sum_{k=1}^K h_k^2},$$

$$\widehat{g(s_2)} = \frac{1}{\sqrt{\rho}} \frac{\sum\limits_{k=1,3,\cdots K} g(r_k)h_{k+1} + \sum\limits_{k=2,4,\cdots K}(g(r_k) - \sqrt{\rho}Ch_k)h_{k-1}}{\sum_{k=1}^K h_k^2}.$$

Since $g(s_l)$ and s_l have one-to-one mapping, s_l is decodable.

B. $M \times N$ OSTBC

In the following, we would prove that (9) can guarantee the symbolwise ML linear decoding of not just the 2×2 Alamouti code, but also any $M \times N$ OSTBC, in FSO MIMO systems. In other words, (9) is the necessary and sufficient condition for generic optical intensity modulation to obtain linear OSTBC decoding complexity.

Based on the transmitted signal matrix defined in [4] [5] for an $M \times N$ OSTBC matrix $\mathbf{X}(s_l)$, (9) generalizes to:

$$g(\bar{\mathbf{X}}(s_l, f(s_l))) = g(\mathbf{X}(s_l)) + C\mathbf{U} \tag{10}$$

where the matrix $\mathbf{U}$ is of dimension $M \times N$ with its (i,j)-th element given by

$$\mathbf{U}_{ij} = \begin{cases} 0, & \text{if } \mathbf{X}_{ij}(s_1 = 1, \cdots, s_L = 1) \geq 0; \\ 1, & \text{otherwise.} \end{cases}$$

At the first PD receiver, the received signal vector is:

$$\mathbf{r} = \sqrt{\rho}\bar{\mathbf{X}}(s_l, f(s_l))\mathbf{h} + \mathbf{z} \tag{11}$$

Applying the post-receiving function $g(\cdot)$ on (11), we obtain

$$\begin{aligned} g(\mathbf{r}) &= \sqrt{\rho} g(\bar{\mathbf{X}}(s_l, f(s_l))\mathbf{h}) + g(\mathbf{z}) \\ &= \sqrt{\rho}(g(\mathbf{X}(s_l)) + C\mathbf{U})\mathbf{h} + g(\mathbf{z}) \\ \Leftrightarrow \quad g(\mathbf{r}) - \sqrt{\rho}C\mathbf{U}\mathbf{h} &= \sqrt{\rho} g(\mathbf{X}(s_l))\mathbf{h} + g(\mathbf{z}) \\ &= \sqrt{\rho}\mathbf{X}(g(s_l))\mathbf{h} + g(\mathbf{z}) \end{aligned} \tag{12}$$

Let $\tilde{\mathbf{r}} \triangleq g(\mathbf{r}) - \sqrt{\rho}C\mathbf{U}\mathbf{h}$ be the received signal vector, $\tilde{s}_l \triangleq g(s_l)$ be the "transformed" information symbols for detection, $\tilde{\mathbf{z}} \triangleq g(\mathbf{z})$ be the channel noise vector, the transmit-receive signal relationship can be reduced as:

$$\tilde{\mathbf{r}} = \sqrt{\rho}\mathbf{X}(\tilde{s}_l)\mathbf{h} + \tilde{\mathbf{z}} \tag{13}$$

We can see that the matrix $\mathbf{X}$ is recovered with orthogonality at the receiver, hence (9) is a sufficient condition for OSTBC to be used in free-space optical channels. Furthermore, $\tilde{s}_l$ can be ML decoded linearly as long as $\mathbf{X}$ is an OSTBC; and s_l can be determined as long as $\tilde{s}_l = g(s_l)$ has a one-to-one mapping to s_l, which is satisfied due to the linearity of $g(\cdot)$ actually.

III. Signal Modulation and Receiver Designs

To apply the OSTBC in FSO MIMO systems with different types of Q-ary intensity modulation, we design, for each modulation type, the non-negative function $f(\cdot)$ and the linear post-receiving function $g(\cdot)$ to satisfy (9). Once $f(\cdot)$ and $g(\cdot)$ are determined, the corresponding constant C can be found.

A. *Q-ary Pulse-Position Modulation (PPM) Scheme*

Assume the transmitted symbols $s_l(t)$ are Q-ary PWM as:

$$s_l(t) = \begin{cases} A, & T_l - \frac{T}{Q} \leq t \leq T_l \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

where $T_l \in \{\frac{T}{Q}, \frac{2T}{Q}, \cdots, T\}$.

Adopt $g_{\text{ppm}}(s_l(t)) = \int_0^T t \cdot s_l(t)\,\mathrm{d}t$ and make it conform to (9), we get

$$g_{\text{ppm}}(s_l(t)) = A(T_l - \frac{T}{2Q})\frac{T}{Q},$$

$$g_{\text{ppm}}(f_{\text{ppm}}(s_l(t))) = -g_{\text{ppm}}(s_l(t)) + C = -A(T_l - \frac{T}{2Q})\frac{T}{Q} + C.$$

Applying $g_{\text{ppm}}^{-1}(\cdot)$, we have

$$f_{\text{ppm}}(s_l(t)) = \begin{cases} A, & T - T_l \leq t \leq \frac{Q+1}{Q}T - T_l \\ 0, & \text{otherwise} \end{cases} \tag{15}$$

and $C = A\frac{T^2}{Q}$. In this scheme, $f_{\text{ppm}}(s_l(t))$, a non-negative PPM symbol, is used in the place of $-s_l(t)$ in the OSTBC matrix.

B. *Q-ary Pulse-Width Modulation (PWM) Scheme*

Assume the transmitted symbols $s_l(t)$ are Q-ary pulse-width modulated, i.e.,

$$s_l(t) = \begin{cases} A, & 0 \leq t \leq T_l \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

where $T_l \in \{0, \frac{T}{Q-1}, \frac{2T}{Q-1}, \cdots, T\}$.

Adopt $g_{\text{pwm}}(s_l(t)) = \int_0^T s_l(t)\,\mathrm{d}t$ and make it conform to (9), we get

$$g_{\text{pwm}}(s_l(t)) = AT_l,$$

$$g_{\text{pwm}}(f_{\text{pwm}}(s_l(t))) = -g_{\text{pwm}}(s_l(t)) + C = -AT_l + C.$$

Applying $g_{\text{pwm}}^{-1}(\cdot)$, we have

$$f_{\text{pwm}}(s_l(t)) = \begin{cases} A, & 0 \leq t \leq T - T_l \\ 0, & \text{otherwise} \end{cases} \tag{17}$$

where $C = AT$. In this scheme, $f_{\text{pwm}}(s_l(t))$, a non-negative pulse-width modulated symbol, is used in the place of $-s_l(t)$ in the OSTBC matrix.

C. *Unified Q-ary PPM-PWM Scheme*

The $g(\cdot)$ functions proposed earlier are different for PPM and PWM, and they both require some form of integration. In this section, we propose a unified $g(\cdot)$ function which does not require integration and can be used for both PPM and PWM. Assume that the transmitted symbols $s_l(t)$ are Q-ary pulse-position modulated, i.e.,

$$s_l(t) = \begin{cases} A, & T_l - \frac{T}{Q} \leq t \leq T_l \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

where $T_l \in \{\frac{T}{Q}, \frac{2T}{Q}, \cdots, T\}$.

Adopt $g_{\text{unif}}(s_l(t)) = s_l(t)$ and make it conform to (9), we get

$$g_{\text{unif}}(f_{\text{unif}}(s_l(t))) = -g_{\text{unif}}(s_l(t)) + C = -s_l(t) + C.$$

Applying $g_{\text{unif}}^{-1}(\cdot)$, we have

$$f_{\text{unif}}(s_l(t)) = A - s_l(t), \quad 0 \leq t \leq T \tag{19}$$

where $C = A$. In this scheme, $f_{\text{unif}}(s_l(t))$, a non-negative pulse-position modulated symbol, is used in the place of $-s_l(t)$ in the OSTBC matrix.

Likewise, for Q-ary pulse-width modulated symbol:

$$s_l(t) = \begin{cases} A, & 0 \leq t \leq T_l \\ 0, & \text{otherwise} \end{cases} \tag{20}$$

where $T_l \in \{0, \frac{T}{Q-1}, \frac{2T}{Q-1}, \cdots, T\}$, the same $g_{\text{unif}}(\cdot)$ and $f_{\text{unif}}(\cdot)$ shown above can be derived and obtained. In fact, the binary PPM in [6] [7] is a special case of the unified PPM-PWM scheme with Q=2.

Examples of s_l and non-negative versions of $-s_l$ for intensity modulations are illustrated in Fig. 2(a) and (b).

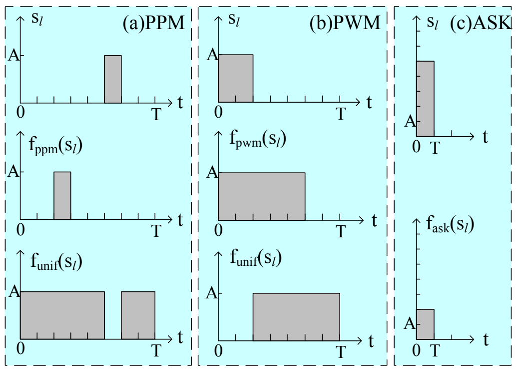

Fig. 2. (a)PPM and unified PPM/PWM schemes with $Q = 8$, $T_l = \frac{6T}{8}$; (b)PWM and unified PPM/PWM schemes with $Q = 8$, $T_l = \frac{2T}{7}$; (c)ASK scheme with $Q = 8$, $q = 6$.

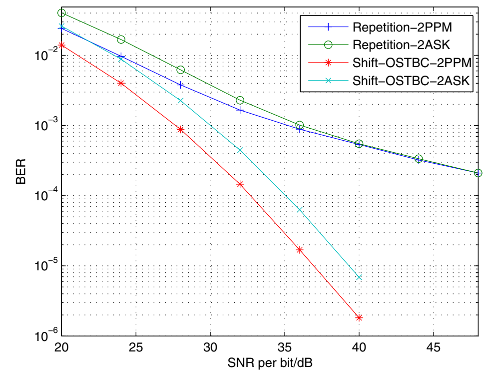

Fig. 3. BER comparison in an asynchronous FSO 2×1 MISO system (1 time-slot misalignment) .

D. Q-ary Amplitude-Shift Keying (ASK) Scheme

In Section III-A, III-B and III-C, constant amplitude intensity modulation has been investigated. To increase the spectrum efficiency, multi-amplitude modulation has been introduced [11] [12]. In the following we shall consider one such case: ASK modulation.

Assume the transmitted symbols $s_l(t)$ are non-negative Q-ary ASK modulated, i.e.,

$$s_l(t) = qA, \quad 0 \le t \le T, \ q \in \{0, 1, \cdots Q-1\} \tag{21}$$

Adopt $g_{\text{ask}}(s_l(t)) = s_l(t)$ and make it conform to (9), we get

$$g_{\text{ask}}(f_{\text{ask}}(s_l(t))) = -g_{\text{ask}}(s_l(t)) + C = -s_l(t) + C.$$

Applying $g_{\text{ask}}^{-1}(\cdot)$, we have

$$f_{\text{ask}}(s_l(t)) = (Q-1)A - s_l(t), \quad 0 \le t \le T \tag{22}$$

where $C = (Q-1)A$. In this scheme, $f_{\text{ask}}(s_l(t))$, a non-negative ASK modulated symbol, is used in the place of $-s_l(t)$ in the OSTBC matrix. An example with $Q = 8$, $q = 6$ is illustrated in Fig. 2(c).

A maximum-likelihood (ML) bit-error ratio (BER) comparison of shift-OSTBC [9] and repetition coding [8], in an asynchronous FSO MISO systems with 2 transmitters and a receiver (in which the signal propagation delay between the second transmitter and the receiver is 1 time slot more than that between the first transmitter and the receiver), is shown in Fig. 3. Two intensity modulation schemes, PPM and ASK, are illustrated. The PWM performance is very similar, hence is omitted. Following [8], the channel is assumed to be log-normal distributed with channel coefficients $h_{kn} = \exp(2\chi_{kn})$ where χ_{kn} is modeled as independent and identically distributed (i.i.d.) Gaussian variables with mean $\mu_\chi = -\sigma_\chi^2$ and variance $\sigma_\chi = 0.5$.

From Fig. 3, we can see that the shift-OSTBC achieves a better performance due to its diversity gain, and because it maintains code orthogonality and hence suffers no inter-symbol interference (ISI), while the repetition coding suffers ISI due to asynchronous reception. Furthermore, the ML decoding complexity of shift-OSTBC increases linearly with the size of signal constellations, but the ML decoding complexity of repetition coding with ISI typically increases exponentially.

IV. Conclusion

In this paper, we design Q-ary (Q arbitrary) intensity modulation schemes for free-space optical OSTBC communications with arbitrary code dimensions by introducing a modulation mapping function $f(\cdot)$ in the transmitter and a linear post-receiving function $g(\cdot)$ in the receiver. Necessary and sufficient condition for the intensity-modulated OSTBC to maintain orthogonality is derived. Finally, the $f(\cdot)$ and $g(\cdot)$ functions that satisfy the necessary and sufficient condition for Q-ary intensity modulation schemes such as PPM, PWM and ASK are formulated. BER performance is verified by simulation in an asynchronous FSO MISO channel setting.

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