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Analysis and Demonstration of Quasi Trace Orthogonal Space Time Block Coding for Visible Light Communications

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ABSTRACT In the VLC context, pulse position modulation (PPM) and similar modulations are typically used when the overall complexity of the transmitter is required to be low or the system needs to support dimming, i.e., dynamically control the illumination level of the transmitter. However, despite the power efficiency of PPM, it is known to be bandwidth inefficient. Having known the trade-off between reliability and spectral efficiency, in this paper we propose a PPM-based space-time block coding (STBC) technique named as quasi-trace-orthogonal (QTO), derived from trace-orthogonal, to increase the spectral efficiency of PPM VLC's by limiting the reliability loss. We provide Monte-Carlo simulations for a 4×4 MIMO-VLC system and validate the results experimentally, and show that for a given signal-to-noise-ratio, the QTO-STBC based 4-PPM VLC system offers higher spectral efficiency at a cost of higher symbol error rate compared to trace-orthogonal STBC.

INDEX TERMS Space time block coding, quasi trace orthogonal, visible light communication.

I. INTRODUCTION

Visible light communications (VLC) is a promising complementary access technology to radio frequency (RF) systems, offering high data rates over a transmission span of a few meters, with low energy consumption and deployment cost as detailed in [1], [2]. In VLC systems with limited transmission bandwidth due to the light emitting diodes, very high data rates are typically achieved by using high order modulations and multicarrier modulation schemes. These are reported in [3] for optical orthogonal frequency-division multiplexing and in [4] for multi-level, amplitude and phase modulation. However, in such schemes the transmit signals can have high peak-to-average power ratio (PAPR) which potentially leads to nonlinear distortions of the signal emitted from the LEDs. Furthermore, DC biasing of the LEDs is a requirement as explained in [5] to ensure both illumination and data communications, which is not strictly necessary in pulse modulation scheme including on-off keying (OOK), pulse position modulation (PPM) etc. In addition both in [6] and [7], OOK and PPM and their variants in conjunction with pulse width modulation (PWM)-based dimming are used for their implementation simplicity. Although PPM is a power efficient modulation scheme, it is bandwidth inefficient thus resulting in lower data transmission rates R_d. Therefore, in order to address the lower data rate feature of PPM as well as improve the VLC link reliability, multiple-input multiple-output (MIMO)-based systems have been investigated and reported widely in the literature [8].

In MIMO VLC links, a number of coding and multiplexing schemes have been adopted. The schemes that employ repetition coding (RC) improve reliability at the expense of reduced spectral efficiency. Spatial multiplexing (SMP) can increase spectral efficiency at the cost of increased error rate. Moreover, other schemes such as spatial modulation (SM) in [9] and space-time block coding (STBC) can balance reliability and spectral efficency. In addition, orthogonal version of STBC (OSTBC) was used to push towards reliability as proposed in [10]. With RC only, as from [11], the code gain (that is the amount of power saving with respect to the

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uncoded case for the same error performance) is achieved at the receiver (Rx) since the transmitter (Tx) sends the same information from the luminaries. With SMP, luminaries emit the independent data streams in order to achieve the maximum multiplexing gain. Whereas in SM, according to what has been done in [12], information is conveyed by both the data symbols modulating the light intensity and the index of the active luminaire. In [13], a performance comparison of RC, SMP and SM in a MIMO VLC system is given, showing that SM is more robust to high channel correlation compared to SMP, while offering higher spectral efficiency compared to RC. However, in order to achieve the same R_d as SMP, SM must have a constellation with very large number of symbols as reported in [14] since when the number of symbols grows the spectral efficiency increases for the same bandwidth level at the expense of reliability as known from communication theory as in [15].

Additionally, in [16] an Alamouti-type STBC for diffuse MIMO-VLC system was introduced using discrete multitone (DMT) modulation. It has been proven that STBC techniques can be used to increase the capacity of diffuse optical wireless systems and decrease the required optical power at the transmitter as well as improve their coverage. STBC-OFDM coding for MISO-VLC is experimentally demonstrated in [17] using two RGB-LEDs and an ADP photodetector, where data rate of 500 Mb/s over 5 m communication distance is achieved. In image-sensor based VLC system, Alamouti-type space time coding has shown to significantly increase the transmission range as done both in [18] and [19]. Finally, in [20] a trace-orthogonal (TO) PPM-STBC for VLC was analytically investigated demonstrating the ability to meet the constraints in terms of BER and R_d (or as alternative the spectral efficiency) by resorting to the trace-orthogonal property of the codewords. However, the achievable spectral efficiency is still very low compared with the SMP based MIMO-PPM systems. About the use of PPM, we remark that it is justified by observing that, with this modulation format, we have some granularity in supporting dimming since this latter equates $1/L$. When we increase the number of transmitting elements (LEDs) the dimming, with respect to the illumination that we can provide with n_T LEDs is still $1/L$ since every LED is on for $1/L$ % of time. On the other hand, if we compare the illumination level of a simple single LED PPM modulation versus the one obtained with the proposed scheme we have n_T/L. This opportunity is not possible with QAM/PAM based STBC schemes since those modulation formats do not support any dimming. As highlighted by the previous detailed literature review, four key aspects are:

- Although PPM is bandwidth inefficient, it is suitable for dimming and reliability;
- O-STBC presents very good performance in terms of reliability even though it is really limited from spectral efficiency point of view, heavy aspect if we consider the above mentioned drawbacks of PPM
- TO-STBC at the cost of lowering the reliability increases a bit the spectral efficiency of the STBC.
- On the other hand SMP is really good from the spectral efficiency point of view at the cost of poor reliability.

Motivated by the above considerations, it appears evident the need of a new STBC that can increase the spectral efficiency even though the reliability can be reduce.

To further improve the spectral efficiency, in this paper we propose and implement a quasi trace orthogonal (QTO)-STBC scheme, which allows more codewords to be transmitted each following a quasi trace orthogonal property. We compare the performance of QTO-STBC by simulations and experimentally with TO-STBC by using a 4×4 MIMO L-PPM VLC system over typical indoor transmission spans of 0.9 m and 1.6 m. We show that QTO-STBC are able to outperform SMP in terms of BER and OSTBC in terms of the spectral efficiency perspective. Basing on the above considerations, it appears clear that in the framework of PPM, that we recall, is a modulation format suitable for reliability and dimming at the expense of spectral efficiency, we want to find out a compromise between two extrema. One is the OSTBC (highly reliable and poorly spectral efficient) and SMP (poorly reliable and good spectral efficient). Hence, in this work we considered a new STBC scheme in the optical wireless panorama that poses itself in between. In particular the contribution can be summarized as

1) proposing a QTO-STBC technique based on the distance among codewords for optical wireless communications, which offers a trade-off between the spectral efficiency and the symbol error rates;
2) considering dimming in the proposed scheme and discussing other opportunities with concurrent systems;
3) providing analytical and simulation results for the proposed method and its competitors;
4) comparing the performance of the proposed method with the TO-STBC counterpart, in terms of symbol error rate and spectral efficiency
5) implementing the proposed system and providing experimental results.

We can anticipate here that the proposed scheme lose a bit in terms of reliability with respect to TO-STBC and OSTBC, even though the gain offered in terms of spectral efficiency, that is, transmission speed, largely counterbalance the limited error rate loss.

The remainder of this paper is organized as follows. The system model is given in Section II, where we introduce the MIMO PPM-STBC architecture and we present the proposed QTO-STBC. In Section IV, numerical and experimental results are given. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

The discrete-time system model of the MIMO-PPM VLC scheme is described in Fig.1. The Tx is characterized by n_T LEDs, each transmitting a PPM symbol of LT_p length, where L is the PPM cardinality, $T_p = T_s/L$ is the PPM slot duration (i.e., the chip time), and T_s is the symbol time. Hence, once defined $p(t)$ as the optical pulse emitted by the LED and the symbol PPM delay ℓT_p, the signal emitted by the j-th LED,

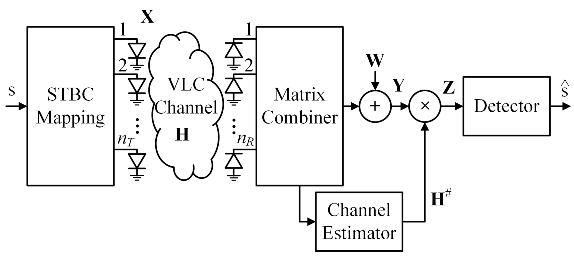

FIGURE 1. The block diagram of the MIMO PPM STBC scheme.

which corresponds to the ℓ-PPM symbol, is given by

$$x_j^{\ell}(t) = p_j(t - \ell T_p), \quad \ell = 0, \ldots, L-1 \tag{1}$$

At the Rx side, n_R photodiodes (PDs) are used each receiving signals from intensity modulated LEDs (i.e., n_T) components. For our porposes, $R[A/W]$ and A_e $[m^2]$ are the responsivity and the effective surface area of the PD, respectively. $h_{ji}(t)$ is the channel impulse response from the j-th transmitting LED to the i-th receiving PD, and $*$ is convolution operator. The term ℓ_j is the pulse position in PPM for the j-th LED while $w_i(t)$ presents the additive white Gaussian noise (AWGN) and possible interfering components due to other light sources. The received signal is:

$$y_i(t) = RA_e \sum_{j=1}^{n_T} x_j^{\ell_j}(t) * h_{ji}(t) + w_i(t) \tag{2}$$

where in a more compact form we have the following positions: $\mathbf{Y}$ is the $[L \times n_R]$ received matrix representing the photocurrent, which is proportional to the L-PPM symbols received by the n_R PDs, and H is a $[n_T \times n_R]$ channel matrix, where each element in the position (j, i) is the path between the j-th transmitting LED and the i-th receiving PD. Hence, considering space and time simultaneously, the discrete-time MIMO sequence is given by:

$$\mathbf{Y} = RA_e\mathbf{XH} + \mathbf{W}, \tag{3}$$

Although the continuous-time model considers the convolution between the emitted signal and the channel, we suppose for our work, to consider the channel with a delay spread that is negligible with respect to signaling time so intersymbol interference does not affect the system. This is verified also by experiments we carried out. Still regarding (3), the term $\mathbf{W}$ is a $[L \times n_R]$ matrix of AWGN, which represents the overall thermal and ambient noise sources (this last is predominant). The information is carried by the STBC $\mathbf{X}$, which is a $[L \times n_T]$ matrix, where the rows and columns represent time dimension (i.e., PPM symbol) and space dimensions, (i.e. n_T), respectively.

The STBC matrix $\mathbf{X}$ to be transmitted is chosen from a set of *codeword* matrices $\mathbf{C}_k$ defined as:

$$\mathbf{C}_k = \left[\mathbf{c}_1^{(k)}\, \mathbf{c}_2^{(k)} \cdots \mathbf{c}_j^{(k)} \cdots \mathbf{c}_{n_T}^{(l)}\right], \tag{4}$$

$$\mathbf{c}_j^{(k)} = \left[c_{1j}^{(k)}\, c_{2j}^{(k)} \ldots c_{ij}^{(k)} \ldots c_{Lj}^{(k)}\right]^T, \tag{5}$$

with $\mathbf{c}_j^{(k)}$ is a $[L \times 1]$ column vector representing the signal emitted by the j-th LED (related to the k-th codeword, under the following two constraints:

$$\sum_{i=1}^{L} c_{ij}^{(k)} = 1, \quad \textit{and} \quad c_{ij}^{(k)} \in \{0, 1\}. \tag{6}$$

The two constraints indicate that, each column vector must contain all "0" with the exception of a single "1". In the case of MIMO SMP, the data streams are transmitted independently from every LED, thus using all the possible MIMO PPM codewords. Given that the maximum number of possible matrix codewords is L^{n_T}, we have $k = L^{n_T} \in \mathbb{R}^+$. Here, we will use a subset of possible matrix codewords $\mathbf{C}_k$ $(k \leq L^{n_T})$ so as to ensure a certain distance between the codewords at the cost of a rate reduction so giving evidence of the well known trade-off between transmission speed and reliability. Note that the requirement for OSTBC is orthogonality among codeword matrices, that is, $\mathbf{C}_m^T\mathbf{C}_k = \mathbf{0}$, $k \neq m$, however here we resort to a different property. This is due to the fact that asking orthogonality from one hand allows high reliability, while on the other hand reduces spectral efficiency since few words (out of L^{N_T}) are mutually orthogonal for assigned number of LEDs and PPM order. For the above reason, we define a STBC as Quasi-Trace-Orthogonal, provided the following constraint is met:

$$\mathrm{Tr}\{\mathbf{C}_m^T\mathbf{C}_k\} = n_T,\, m = k \text{ and } \mathrm{Tr}\{\mathbf{C}_m^T\mathbf{C}_k\} \leq \xi, \quad m \neq k \tag{7}$$

There is a trade-off between the spectral efficiency and the BER, which can be achieved by setting the parameter ξ. Hence, from (7) we can conclude that, (i) a set of codewords will include the combinations of matrices with the trace distances equal or less ξ; and (ii) the same index $(k \neq m)$ should not be considered. Thus, ξ is set as:

$$0 \leq \xi < \lfloor \log_2 n_T \rfloor. \tag{8}$$

Note, by increasing the number of Txs we have a higher value for ξ, since the range increases with n_T. We recall that, for $\xi = 0$ we obtain TO-STBC as in [20]. It is important to highlight that, by increasing the number of LEDs the number of codewords with increased distance, in terms of trace, increases is higher. Hence, a higher number of codewords can meet the constraints, thus leading to higher spectral efficiency. Following [20], once defined Q ss the number of codewords meeting the QTO constraint, which is upperbounded by L^{n_T} and corresponds to the case of SMP so leading to $\eta = (n_T \log_2 L)/L$, the spectral efficiency of a STBC is defined as:

$$\eta = \frac{\log_2 Q}{L} \tag{9}$$

As in [20], at the Rx side, data detection is performed following spatial zero forcing equalization, which utilized $\mathbf{H}^\sharp$ that is the inverse (or pseudo inverse when $n_T \neq n_R$) channel matrix:

$$\mathbf{Z} = \mathbf{YH}^\sharp = \mathbf{X} + \mathbf{WH}^\sharp. \tag{10}$$

The decision between the possible transmitted codeword has the following form:

$$\widehat{\mathbf{C}} = \arg\max_{k} \mathrm{Tr}\{\mathbf{C}_m^T \mathbf{Z}\}. \quad (11)$$

About $\mathbf{H}^\sharp$, it can be obtained by transmitting training symbols every N_d information data symbols. The training symbols have the form of identity STBC matrix. Till now, we assume that the channel is known perfectly and the channel inversion (that is a spatial zero-forcing (ZF) equalization) is able to perfectly act as countermeasure of channel crosstalk. Besides, we need to state that, even though it is known that ZF equalization can lead to noise amplification, it suffices to space apart LEDs and PDs in order to obtain a full rank matrix with no noise amplification. In order to focus on a more realistic scenario we must provide information on the channel with mobility for the purposes of for channel acquisition and estimation by transmitting a training sequence $\mathbf{X}_T$ represented by the following identity matrix with n_T rows and columns:

$$\mathbf{X}_T = \begin{bmatrix} 1 & 0 & \dots & 0 & 0 \\ 0 & 1 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & 1 & 0 \\ 0 & \dots & \dots & 0 & 1 \end{bmatrix} = \mathbf{I}_{n_T} \quad (12)$$

Note, this may be in contradiction with (3), since the matrix $\mathbf{X}$ has L rows. However, the symbol emitted here are not used for data detection since the received matrix is given by:

$$\mathbf{Y} = RA_e\mathbf{H} + \mathbf{W} \quad (13)$$

This means that the observed sequence is a collection of noisy samples representing the channel coefficients.

III. THEORETICAL RESULTS

By comparing the results offered by the above mentioned schemes that are, OSTBC, SMP, TO-STBC and the proposed QTO-STBC we can consider the behaviour of the Maximum likelihood (ML) detection for an assigned channel, thus meaning that the error probability is conditioned to the channel realization. Starting from the analytical derivations carried out in [20] under very general conditions, we can specify them for the cases of interest. So we have for TO-STBC that the error probability can be upper-bounded as

$$\begin{aligned} P_e(\text{TO-STBC}) &= \Pr\{\hat{\mathbf{X}} = \mathbf{C}_j|\mathbf{C}_i, \mathbf{H}\} \\ &\leq \Pr\{\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\mathbf{H}^\sharp\} > n_T + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\mathbf{H}^\sharp\}\} \end{aligned} \quad (14)$$

while for the case of OSTBC the same procedures leads to

$$\begin{aligned} P_e(\text{OSTBC}) &= \Pr\{\hat{\mathbf{X}} = \mathbf{C}_j|\mathbf{C}_i, \mathbf{H}\} \\ &\leq \Pr\{\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\} > n_T + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\}\}. \end{aligned} \quad (15)$$

Regarding SMP, the error probability is given by

$$\begin{aligned} P_e(\text{SMP}) &= \Pr\{\hat{\mathbf{X}} = \mathbf{C}_j|\mathbf{C}_i, \mathbf{H}\} \\ &\leq \Pr\{\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\mathbf{H}^\sharp\} > 1 + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\mathbf{H}^\sharp\}\} \end{aligned} \quad (16)$$

while for the proposed QTO we have

$$\begin{aligned} &P_e(\text{QTO-STBC}) = \Pr\{\hat{\mathbf{X}} = \mathbf{C}_j|\mathbf{C}_i, \mathbf{H}\} \\ &\leq \Pr\{\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\mathbf{H}^\sharp\} > n_T - \lfloor\log_2 n_T\rfloor + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\mathbf{H}^\sharp\}\} \end{aligned} \quad (17)$$

Looking at the four expression it appears clear why QTO-STBC outperforms SMP. We have the same term on the left hand side for all the expressions, that is $\{\mathbf{C}_j\mathbf{W}\mathbf{H}^\sharp\}$. In particular, for QTO in (17) the error event requires that $\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\mathbf{H}^\sharp\} > n_T - \lfloor\log_2 n_T\rfloor + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\mathbf{H}^\sharp\}$ while for SMP the error events occur when $\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\mathbf{H}^\sharp\} > 1 + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\mathbf{H}^\sharp\}$. Following the same logical line, the performance offered by TO-STBC are better form the error rate point of view since this latter is less probable since an error occurs when $\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\mathbf{H}^\sharp\} > n_T + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\mathbf{H}^\sharp\}$. The diminishing term on the right hand side $\lfloor\log_2 n_T\rfloor$ is missing now. Last, the comparison of QTO-STBC and OSTBC is in favour of this latter since its performance are related, as error event, to the occurrence of the inequality $\mathrm{Tr}\{\mathbf{C}_j^T\mathbf{W}\} > n_T + \mathrm{Tr}\{\mathbf{C}_i^T\mathbf{W}\}$ that is less probable with respect to that of TO-STBC, QTO-STBC and SMP since it involves not the pseudo-inverse matrix (containing values higher than one) but only small values due to noise matrix.

IV. SYSTEM IMPLEMENTATION

In this section, we present both simulation results and validate them experimentally. For simulations we used the channel measures so the signal generated with Matlab software is filtered by measured channel and noise added artificially so as to perform error rate. For what concerns tests, the LEDs we considered emitted the signals according to the QTO scheme we proposed and we off-line processed the received and acquired signal that takes into account also the ambient lighting as additional interference term. Table 1 reports all the key parameters that were used in simulation and experiment.

TABLE 1. Key parameters for the experiments.

Parameters	Values
Transmitter	
Bias current per LED	350 mA
Transmit power per LED	175 mW
Beam angle	120°
Bandwidth	1.9 MHz
Number of LEDs in Tx	4
LED pitch	2 cm
Amplifiers gain	4.7dB
Receiver	
PD bandwidth	29 MHz
FoV	140Âř
Number of PDs in Rx	4
PD pitch	1 cm
Lens diameter	10 cm
Lens focal length	20 cm

The performance of both TO-STBC and the proposed QTO-STBC are evaluated and compared, experimentally for $n_T = n_R = 4$. We point out, as known from the MIMO theory, that in order to obtain spatial diversity, the Txs (i.e., LEDs) and the Rxs (i.e, PDs) should be sufficiently spaced so as to

TABLE 2. Spectral efficiency η and BER (β) at SNR of 13dB for SMP, QTO, TO and OSTBC.

	2-PPM	4-PPM	8-PPM
SMP	$\eta = 2$ $\beta = 6.5 \cdot 10^{-3}$	$\eta = 2$ $\beta = 1.05 \cdot 10^{-3}$	$\eta = 1.5$ $\beta = 1.67 \cdot 10^{-4}$
QTO	$\eta = 1.5$ $\beta = 2.3^{-3}$	$\eta = 1.5$ $3.5 \cdot 10^{-4}$	$\eta = 1.375$ $3.5 \cdot 10^{-5}$
TO	$\eta = 0.5$ $\beta = 8.4 \cdot 10^{-4}$	$\eta = 0.5$ $\beta = 1.3 \cdot 10^{-4}$	$\eta = 0.375$ $\beta = 1.66 \cdot 10^{-5}$
OSTBC	$\eta = 0.5$ $\beta = 4.9 \cdot 10^{-4}$	$\eta = 0.5$ $\beta = 5.5 \cdot 10^{-5}$	$\eta = 0.25$ $\beta = 7.3 \cdot 10^{-6}$

guarantee independence among the channels. In the proposed system, by fixing the LEDs spacing to 2 cm and changing the PDs spacing we have non-monotonic behavior. In fact, a closer spacing of LEDs and PDs results in increased SNR because of the reduced transmission span. However, increasing the spacing between PDs (i.e., improved diversity as well as increased the propagation path) with result in reduced received optical power and consequently lower SNR. Table 2 shows the spectral efficiencies (i.e., data rates) for SMP, QTO, TO and OSTBC and the bit error rates (BER) for a SNR of 13 dB. We note the following observations for the spectral efficiency (η) and symbol error rate (β). Considering moving vertically from SMP to OSTBC for the assigned PPM order, the spectral efficiency (bits/s/Hz) is decreased from 2 to 0.5 (i.e., $L = 2$) and 1.5 to 0.25 (i.e., $L = 8$). The QTO performance are not so close to SMP since the difference are 1.5 and 1.375 compared with 2 ($L = 2$) and 1.5 ($L = 8$). Note, for $L = 8$ QTO offers 4 times the efficiency compared to TO. Note that, both OSTBC and offer much lower spectral efficiencies compared to SMP and QTO. As for the SER, we can observe that SMP does not perform very well while OSTBC is the best performance. The performance of QTO and TO are in between.

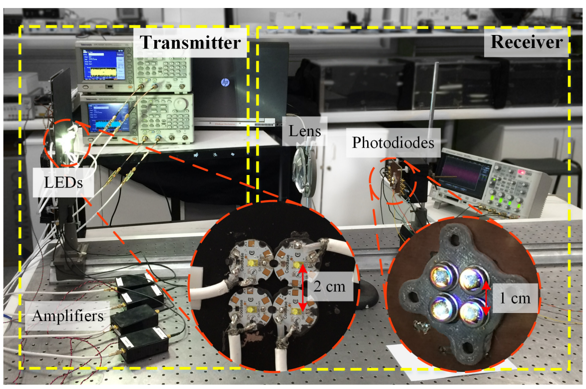

FIGURE 2. Experimental setup for the proposed system and the LEDs and photodiodes shown in the inset.

Figure 2 depicts the experimental setup of the proposed 4×4 MIMO-VLC L-PPM system. At the Tx, a pseudo random binary sequence (PRBS) in the L-PPM format was generated in MATLAB and stored in order to allow error rate evaluation by comparing sequences of bits. Two identical AFG3252C arbitrary function generators (AFGs) with a chip frequency ($1/T_p$) of 1 MHz were used to generate the L-PPM signals which were pre-amplified (with a gain of 5 dB) prior to intensity modulation of LEDs (4 cool white 5650K LUXEON Rebel LEDs) using a bias tee circuit. Note, the distance between two adjacent LEDs is 2 cm. The cardinality of the PPM is equal to 4 ($L = 4$), thus a matrix of the transmitted codeword $\mathbf{X}$ is of a size of $[4 \times 4]$.

At the Rx, a convex lens was used in order to focus the received optical beams onto 4 PDs (silicon PD OSD15-5T). The diameter and the focal length of lenses were 11 cm and 20 cm for the link span (L_s) of 0.9 m, and 11 cm and 35 cm for L_s of 1.6 m, respectively. The distances between the Tx and the lens, and between the lens and the optical Rx were 60 cm and 30 cm, for L_s of 0.9 m, and 105 cm and 55 cm for L_s of 1.6 m, respectively. Following optoelectronic conversion and amplification using transimpedance amplifiers (TIAs), the regenerated electrical signals were captured using a DSO-X3034A digital storage oscilloscope with a sampling rate of 50MS/s for off-line processing and spatial equalization and decision with Matlab scripts as in (11).

A. RESULTS AND DISCUSSIONS

Using the experimental setup, we carried out measurements for the proposed scheme.

Note that, the noise sources considered are the background induced noise and thermal noise in order to represent the worst case scenario. Hence, once defined I_{bg} [A] as the background current, Δf [Hz] the PD bandwidth, q electron charge, k_p [JK^{-1}] Boltzmann constant, T [K] the temperature and R_f [Ω] amplifier feedback resistance, with values reported in [20], the whole noise is given by

$$\mathcal{N} = 2qI_{\text{bg}}\Delta f + 4k_pT\Delta f/R_f. \tag{18}$$

From (18), it follows that, $P_r^{(\text{opt})}$ being the received optical power the signal to noise ratio (SNR) is defined by:

$$SNR = \frac{(RP_r^{(\text{opt})})^2}{2qI_{\text{bg}}\Delta f + 4k_pT\Delta f/R_f}. \tag{19}$$

The channel used in the simulation is numerically obtained from the experiments measurement using the set-up introduced in the previous subsection, with the Rx placed at 1.6 m from the Tx. As for the channel impulse response, $N_d = 5$ identity matrices $\mathbf{I}_4$ were transmitted, and using the channel estimation procedures detailed before, estimated matrix is given by:

$$\hat{\mathbf{H}} = \begin{bmatrix} 0.838 & 0.084 & 0.083 & 0.0126 \\ 0.168 & 0.628 & 0.008 & 0.0126 \\ 0.084 & 0.075 & 0.754 & 0.04 \\ 0.083 & 0.073 & 0.084 & 0.59 \end{bmatrix} \tag{20}$$

Note that, the use of a lens at the Rx introduces a low level of inter-channel interference. Fig. 3 shows the Monte-Carlo simulation results for the BER versus the SNR for TO and QTO-STBC VLC systems.

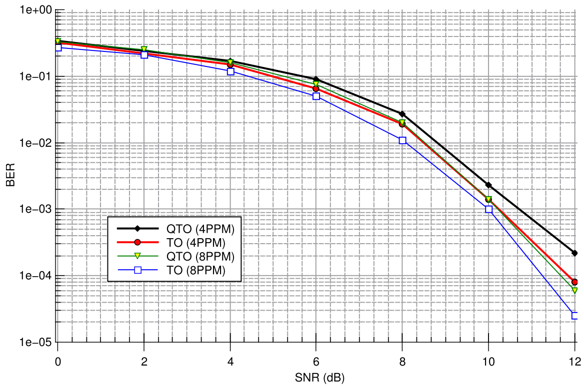

FIGURE 3. Simulated SER vs. SNR for Trace-Orthogonal vs Quasi Trace-Orthogonal STBC for a link span of 1.6 m.

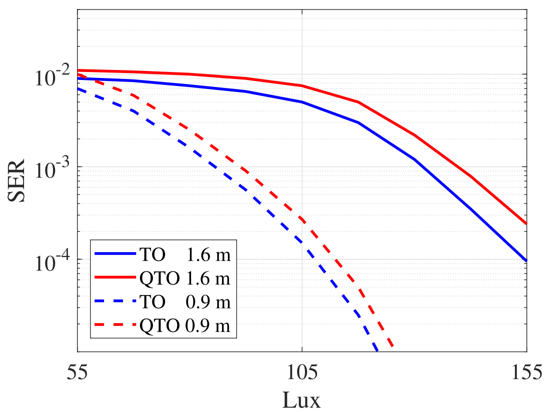

FIGURE 4. SER vs. luminous experiment for L_s of 0.9 and 1.6 m and for trace-orthogonal vs quasi trace-orthogonal STBC-based 4 × 4 MIMO 4-PPM VLC systems.

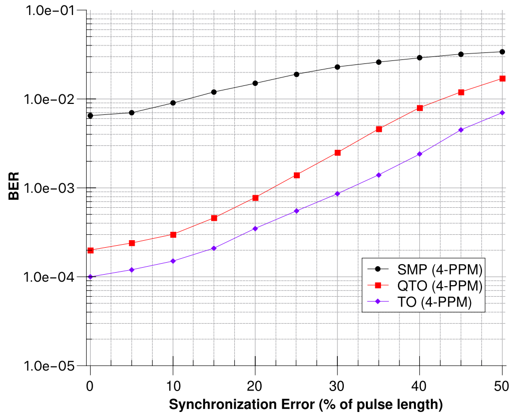

FIGURE 5. BER as a function of mistiming for QTO, TO, and SMP.

As expected, TO-STBC offers marginally improved BER performance compared to QTO-STBC. For example, for a SER of 10^{-3} there is only 0.25 dB of difference between the two schemes. However, QTO-STBC offers three times the data rate compared with TO-STBC for 4-PPM, see Table 2.

Fig. 4 illustrates the measured SER as a function of the luminous flux for both TO- and QTO-STBC VLC systems with link distance of 0.9 m and 1.6 m. Note that two streams of data were transmitted preceded by $N_d = 5$ identity matrices for channel estimation and synchronization purposes. As shown, the experimental result also confirms that TO-STBC slightly outperform the QTO-STBC scheme from the SER point of view, e.g., for $L_s = 0.9$ m and for a luminous level of 56 lux, the SER are $9 \cdot 10^{-3}$ and $8 \cdot 10^{-3}$ for TO and QTO, respectively, which increases to $3.5 \cdot 10^{-2}$ and $6 \cdot 10^{-2}$ for L_s of 1.6 m. However, when 4-PPM is used QTO-STBC presents $\eta = 1.5$bit/s/Hz while TO-STBC offers $\eta = 0.5$bit/s/Hz. Hence, the slight loss of QTO-STBC is largely compensated by the gain of spectral efficiency.

Last, regarding synchronization, we test the performance of QTO, TO and SMP when the error in acquiring timing ranges from 0% to 50% of the pulse length. We consider the case of SNR equating 12dB in the case of perfect synchronization and report the results in Fig.5 when the modulation format for space-time coding used is 4-PPM. It is important to note the strong difference from TO and QTO from one hand, and SMP. In fact, also in the case of perfect synchronization, the distance in terms of BER is noticeable due to the minimum distance among codeword that, in the case of SMP, is the smallest. Moreover, when the mistiming effect raises, the BER increases till to have a quasi-flat behaviour when it approaches 50% of pulse length. It is worth highlighting that, although TO outperforms QTO in terms of BER, as previously disclosed, the difference in terms of rate for 4-PPM is in advantage of QTO since it has a spectral efficiency that is three times the one exhibited by TO. From this we can observe as QTO is a good compromise between rate and error rate with respect to other STBC methods.

V. CONCLUSION

In conclusion, we presented a quasi QTO-STBC technique in which the trace-orthogonal constraint imposed for the transmitted STBC codewords is less stringent, thus leading to a higher spectral efficiency (i.e., higher multiplexing gain) in the MIMO scheme. We carried out Monte-Carlo simulations and experimentally evaluated both schemes adopted in a 4 × 4 MIMO L-PPM VLC system and showed that QTO allows to increase spectral efficiency with respect to TO till to 4 times when 8-PPM is used at the cost of a doubled error probability.

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