Contrasting Space-Time Schemes for MIMO FSO Systems with Non-Coherent Modulation

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***Abstract*—For the case of multiple-input multiple-output (MIMO) free-space optical (FSO) communication systems, we consider the suitability of the spatial multiplexing scheme when on-off keying modulation is employed. We show that, even with the optimal maximum likelihood detection at the receiver, the performance is worse, compared to the case of repetition coding (RC) under the condition of equal transmission rate. This confirms the quasi-optimality of the RC scheme for MIMO FSO systems.**

I. Introduction

Free-space optical (FSO) communication is well known for its advantages of license-free spectrum, high data-rate, low energy consumption, and inherent security, compared to radio frequency (RF) systems [1]. In near-ground FSO systems, one of the principal channel impairments is the atmospheric turbulence which induces intensity fluctuations at the receiver that can considerably degrade the system performance [2]. One solution for fading mitigation is aperture averaging [3]. However, when working at long link distances, the required collecting lens for efficient fading reduction becomes too large [4]. Under such conditions, spatial diversity is a more suitable solution [5]. In particular, significant fading reduction can be obtained through the use of multiple apertures at the receiver and multiple beams at the transmitter [6], [7]. For these multiple-input multiple-output (MIMO) systems, one important question is how to combine the information-bearing symbols at the transmitter in order to optimize the system performance, what is classically called space-time (ST) coding. This is an extensively-developed subject in RF systems. Here, we focus on the spatial multiplexing (SMux) scheme, where the information bearing signals are just multiplexed at the transmitter. The interest of SMux is that it has the maximum transmission rate. Our aim is to investigate the practical interest of this scheme by taking into account the receiver performance and its computational complexity.

In the remainder of the paper, we first present a state-of-the-art on ST coding in MIMO FSO systems and explain the idea behind this work. General assumptions on the channel model and signal transmission are then described in Section III. Then, we present some numerical results on the performance comparison of different ST schemes in Section IV. Finally, Section V concludes the paper.

II. Space-time coding for MIMO FSO systems

In fact, most of the proposed ST schemes for RF applications use phase rotation and amplitude weighting [8], [9], [10], requiring at least bipolar signaling when applied to the FSO context. In general, the ST schemes optimized for RF systems provide full diversity in FSO systems but are not optimized concerning the coding gain [11]. ST schemes can be classified into orthogonal and non-orthogonal schemes. Orthogonal schemes, which usually provide full diversity, have received more attention because of their low-complexity optimal detection [9]. Non-orthogonal schemes are generally designed to optimize both diversity and coding gains and have mostly a better performance than their orthogonal counterparts [12]. They have also shown to be more robust against channel turbulence when using coherent modulations [13]. However, their optimal detection is of high computational complexity. Also, they can not be used in the FSO systems using intensity modulation with direct detection (IM/DD).

In classical MIMO FSO systems, one does not do any ST coding at the transmitter and the same symbol is sent over the multiple beams. This is usually referred to as repetition coding (RC) [14]. On the other hand, most of the orthogonal ST block codes (OSTBCs) can be modified to be adapted to IM/DD FSO systems. For instance, for the case of two transmitter beams, a modified Alamouti scheme [15] is proposed in [16] which is adapted to IM/DD optical systems by introducing a bias to overcome unipolar signaling used in these systems. This idea is then generalized in [17] to ON-OFF keying (OOK) modulation with any pulse shape. In fact, Both RC and OSTBCs provide full diversity but RC is shown to outperform the latter, and the performance gap increases with increased number of transmitter beams [18].

In fact, RC seems to be quasi-optimum, as explained in [11]. However, it is of rate one and does not exploit the MIMO channel to increase the transmission rate. On the contrary, SMux maximizes the transmission rate but at the expense of reduced diversity gain. Recently, a new ST scheme, called optical spatial modulation (OSM) has been proposed by which only one ON symbol is transmitted from the M beams at a given channel use [19], [20] so as to avoid inter-channel interference. The ST coding rate of OSM is $\log_2 M$ symbols per channel-use. At the receiver, optimal maximum likelihood detection (MLD) can be used to estimate the corresponding beam [21].

Here, we are specially interested to investigate the usefulness of SMux in FSO systems. We know from previous works on RF MIMO systems that the simple linear detection methods like the minimum mean-squareerror (MMSE) detection do not provide a satisfying performance. An interesting linear and low-complexity receiver is the vertical BLAST (V-BLAST) architecture [22]. This method uses successive interference cancelation and signal detection based on zero-forcing (ZF) or MMSE criterion and has been shown to have a significantly better performance than the simple ZF or MMSE detectors. It is not clear whether or not for OOK modulation this method preserves its interest, however. Also, it is known that for M transmitters and N receivers, V-BLAST detection can benefit from a diversity of $N - M + 1$ [23], and consequently, it is practically interesting only when $N > M$. This is not usually the case in most FSO systems, however, as we have $M = N$ in most systems. To partially circumvent this problem, it is proposed in [24] for $M > 2$ to consider pairwise Alamouti coded transmitted symbols and to perform QR decomposition of the fading channel at the receiver.

Our aim is to consider the SMux and OSM schemes at the transmitter and to compare their performance with RC and OSTBC. In order to make a fair comparison, we fix the total data transmission rate for all cases. For this, we reduce the symbol duration for RC, OSTBC, and OSM schemes accordingly. For the case of SMux, we consider different detection methods including the optimal MLD to investigate the receiver performance, regardless of the computational complexity issues.

III. Channel model and assumptions

We consider the use of a Gaussian beam at the transmitter and a PIN photodiode at the receiver and assume that the dominant receiver noise is the thermal noise. This is modeled as additive white Gaussian with the unilateral power spectral density N_0. We consider a single-beam single-aperture system of aperture diameter 200 mm as reference and denote its receiver noise variance by σ_n^2. We denote this system by SISO (for single-input single-output). When using multiple apertures, the noise variance is considered the same at each receiver whatever its aperture size is. For channel turbulence modeling, we consider the Gamma-Gamma distribution by which the normalized received intensity is considered as the product of two independent random variables, representing the large- and small-scale irradiance fluctuations, respectively [25]. For $(M \times N)$ MIMO structure, we assume that the spacings between the transmitter beams and the receiver apertures are large enough so as to ensure independent fading between the underlying sub-channels. Also, we assume we have perfect channel knowledge at the receiver.

We consider a diverging Gaussian beam at $\lambda = 1550\,\text{nm}$ of beam waist $W_0 = 1.59\,\text{cm}$ and the curvature radius of the phase front of $F_0 = -69.9\,\text{m}$. Concerning the channel turbulence, we set $C_n^2 = 6.5 \times 10^{-14}\,\text{m}^{-2/3}$ and the inner and outer scales of turbulence of $l_0 = 6.1\,\text{mm}$ and $L_0 = 1.3\,\text{m}$. These parameters correspond to the experimental works reported in [3]. The link distance is given as $L = 5\,\text{km}$ for which the Rytov variance $\sigma_R^2 = 24.7$. We use the uncoded OOK modulation and fix the total receiver aperture diameter to $D_r = 200\,\text{mm}$.

To make a fair comparison between the performances of different ST schemes, we fix the average transmit optical power P_{av}. Considering OOK modulation, this corresponds to a peak optical intensity of $P_t = 2P_{av}$ in On slots for the reference SISO system, for example. For the case of MIMO systems, the peak intensity at each transmitter is set to P_t/M, except for OSM where it is set to $P_t/(\log_2 M)$. Also, we set the diameter of each aperture to $D_r/\sqrt{N}$ so as to fix the total received intensity. Furthermore, we fix the transmission rate for the different systems and denote it by R_b. Accordingly, for the MIMO case, we set the pulse duration to $1/R_b$ for the cases of RC and OSTBC, and to M/R_b and $(\log_2 M)/R_b$ for the SMux and OSM cases, respectively.

IV. Numerical results

Here we present some simulation results to compare the performances of the different ST schemes. The performance is considered as the bit-error-rate (BER) versus the electrical signal-to-noise ratio (SNR) in the form of E_b/N_0, with E_b being the average total received energy per information bit. We have $E_b = P_t^2/2R_b$, $N_0 = 2\sigma_n^2/R_b$. For signal detection at the receiver, we consider MLD for all schemes, as well as simple MMSE and MMSE V-BLAST for SMux. We also present the BER performance for the reference SISO system for the sake of completeness. We consider two case studies of $M = N = 2$ and $M = N = 4$ in the following.

A. Case of (2×2) FSO system

The performance of RC, OSTBC, OSM, and SMux schemes are compared in Fig. 1. As OSTBC, we consider the modified Alamouti scheme, proposed in [16]. We notice that the RC scheme remains the best. For instance, at BER$=10^{-4}$, MMSE V-BLAST detection provides 7 dB gain in SNR, compared to simple MMSE. However, the MMSE V-BLAST performs 30 dB worse than the optimal MLD detection. We notice that the performances of OSM and SMux with MLD are very close. On the other hand, the rate-one schemes, i.e., RC and OSTBC, perform much better than OSM and SMux with MLD detection. Remember that for these schemes, we use half the symbol duration of the SMux case so as to have the same total transmission rate. In fact, although dividing the symbol duration results in an increase of factor 2 in the receiver thermal noise variance, compared to the SMux case, the overall performance is still better than this latter case. Another interesting point is that RC and OSTBC outperform the reference SISO system only at low BER. This is due to the trade-off between aperture averaging and spatial diversity and also the increased total receiver noise in MIMO systems.

B. Case of (4×4) FSO system

Figure 2 contrasts the performances of RC, OSTBC, OSM, and SMux schemes. As OSTBC, we consider the Jafarkhani's scheme [26] that we modify in the same way as it is done in [16] to adapt it to OOK modulation. Note that this scheme is orthogonal for this case. We notice again that RC is preferred to OSTBC and OSM,

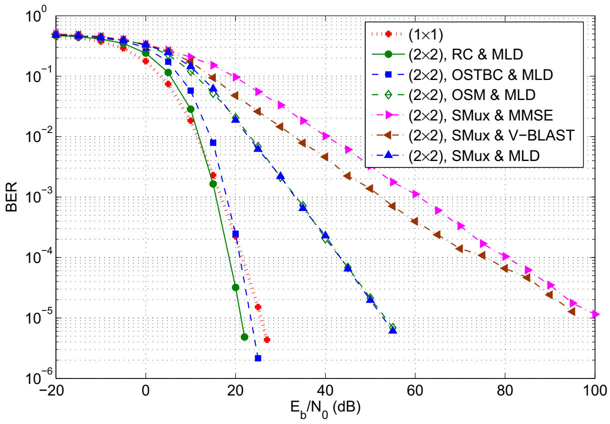

Fig. 1. Contrasting BER performance of different ST schemes for a (2×2) MIMO FSO system. $Z = 5\,\mathrm{Km}$, $D = 200\,\mathrm{mm}$. Uncoded OOK, thermal noise limited receiver.

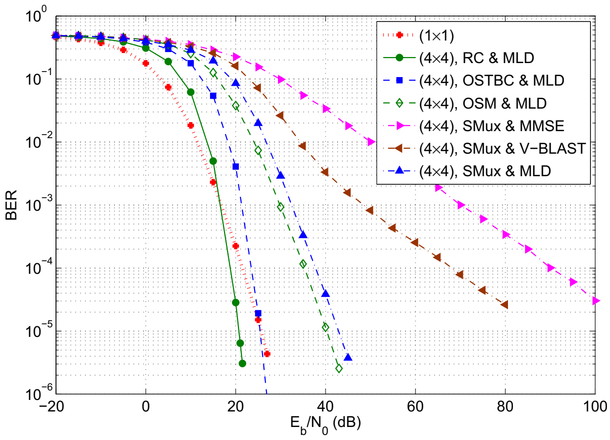

Fig. 2. Contrasting BER performance of different ST schemes for a (4×4) MIMO FSO system. $Z = 5\,\mathrm{Km}$, $D = 200\,\mathrm{mm}$. Uncoded OOK, thermal noise limited receiver.

and also to SMux even with MLD. Note that OSM here outperforms SMux-MLD.

V. Conclusion

We investigated the interest of SMux in MIMO FSO systems and compared its performance to those of RC, OSTBC, and OSM. Our study confirmed the quasi-optimality of the full-diversity RC scheme due to its lower complexity and better performance, compared to the other ST schemes. We conclude from our study that when a higher data rate is required, it is preferable to directly reduce the symbol duration instead of resorting to a higher rate ST scheme like SMux.

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