Mode Vector Modulation Direct-Detection Receivers with Linear Hardware Complexity

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ABSTRACT—*We propose a polarimetric direct-detection receiver design, which measures amplitude and phase information sent over a spatial superchannel. The number of photodiodes in our optimized design scales linearly with the spatial degrees of freedom. ©2022 The Author(s)*

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I. INTRODUCTION

The design of self-homodyne receivers[1]–[3], especially when used with spectrally- and energy-efficient higher-dimensional modulation formats, has been an active area of research in optical communications. Stokes-vector receivers have particularly drawn significant interest[1]. The concept of Stokes-vector detection was recently extended to multimode optical fibers[4]. To distinguish it from its single-mode-fiber counterpart, we shall refer to such a receiver as a *mode-vector (MV) direct-detection (DD) receiver*. Mode Vector Modulation (MVM), a generalization of Stokes vector modulation (SVM) to multimode/multicore optical fibers or free space[5],[6], is one possible use of MV receivers.

A naive design of a MV receiver which detects generalized Stokes vectors over N spatial and polarization degrees of freedom would require $(2N^2-N)$ identical photodiodes, leading to quadratically-scaling complexity and cost. In this paper, we propose an optimized MV direct-detection receiver architecture that leverages the interdependence of the generalized Stokes parameters, showing that $(5N-4)$ photodiodes is sufficient to estimate the generalized Stokes parameters of the spatial superchannel.

II. PROPOSED RECEIVER ARCHITECTURE

Expressing the (N^2-1) generalized Stokes components in terms of the $2N$ complex Jones components, we find three distinct forms, as listed in Fig. 1a. The receiver's optical front-end is designed to measure the constituent terms of these equations, which are subsequently provided to the digital signal processing (DSP) unit that computes the Stokes components.

Analyzing the calculation of the first two Stokes parameter types in Fig. 1a, we must compute the real and imaginary parts of the quantity $s_i s_j^*$ for a pair of Jones components s_i, s_j. This can be accomplished with a $90°$ optical hybrid followed by a pair of balanced receivers[7]. Additionally measuring $|s_i|^2$ and $|s_j|^2$ for computing the third type of Stokes components in Fig. 1a leads us to the unit cell of Fig. 1b. When necessary, polarization controllers are used to align the states of polarization of the $i-$th and $j-$th Jones components before the optical hybrid.

It might initially seem that $N(N-1)/2$ such unit cells are necessary to analyze all pairs $s_i s_j^*$, but two distinct products $s_i s_j^*$, $s_j s_k^*$ share common information as they are both dependent on the Jones component s_j. As such, we need only $(N-1)$ unit cells to measure the characteristic quantities $|s_i|^2$, $|s_{i+1}|^2$, $\Re\{s_i s_{i+1}^*\}$, and $\Im\{s_i s_{i+1}^*\}$ for $i = 1,\dots,N-1$. The DSP can then compute $|s_i|$, $|s_{i+1}|$, and $s_i s_{i+1}^* = \Re\{s_i s_{i+1}^*\} + i\Im\{s_i s_{i+1}^*\}$, which in turn gives the differential phases $\theta_{i,i+1} := \theta_i - \theta_{i+1} = \arg(s_i s_{i+1}^*)$. We can thus recover all the pairs $s_i s_j^* = \exp(i\theta_{i,j})|s_i||s_j|$, where $\theta_{i,j} := \theta_{i,i+1} + \cdots + \theta_{j-1,j}$ for $i < j$.

These simplifications lead us to the MV DD receiver architecture shown in Fig. 1c. The hardware implementation requires cascading $(N-1)$ unit cells, similar to the one shown in Fig. 1b. While six photodiodes are necesary for the first unit cell, the remaining $(N-2)$ unit cells only require five photodiodes. Thus, a total of $(5N-4)$ photodiodes are sufficient to measure the (N^2-1) generalized Stokes components, giving a linearly-scaling front-end complexity with respect to the number of spatial and polarization degrees of freedom. The number of necessary photodiodes can be further reduced to $(3N-2)$ by resorting to only single-ended detection for outputs 2 and 3 of each unit cell to absolutely minimize the hardware complexity.

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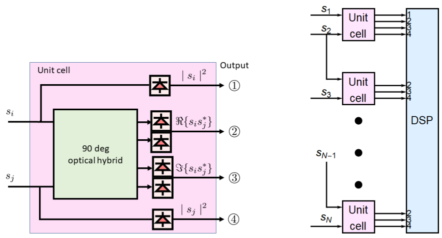
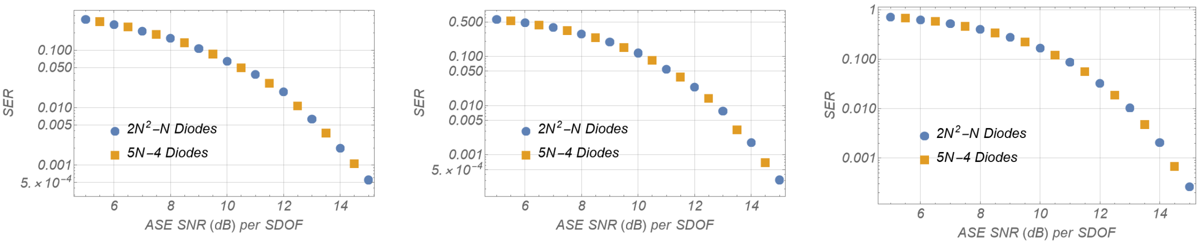
Number of terms	Expression
$\frac{N(N-1)}{2}$	$S_k = 2C_N\Re\{s_i s_j^*\}$
$\frac{N(N-1)}{2}$	$S_k = -2C_N\Im\{s_i s_j^*\}$
$N-1$	$S_k = C_N\sqrt{\frac{2}{\ell(\ell+1)}} \cdot \left(\sum_{j=1}^{\ell}\lvert s_j\rvert^2 - \ell\lvert s_{\ell+1}\rvert^2\right)$

(a)



(b) **(c)**

Figure 1: (a) Stokes parameters expressed in terms of the Jones vector components; (b)-(c) Schematics of the proposed optically-preamplified MV DD receiver: (b) Unit cell; (c) Cascaded architecture.



(a) $(2,4)$-MVM **(b)** $(4,16)$-MVM **(c)** $(8,64)$-MVM

Figure 2: Performance comparison of MV receivers with $O(N)$ and $O(N^2)$ hardware complexity: SER vs ASE noise symbol SNR per SDOF for SIC-POVM based MVM constellations in dimensions $N = 2, 4, 8$.

III. Results and Discussion

One might initially suspect that our linear-hardware-complexity MV receiver of the previous section will be prone to the accumulation of numerical errors in the estimation of the generalized Stokes components as several noisy measurements are combined to calculate the $s_i s_j^*$ terms. To test this hypothesis, we simulated both the linear-complexity receiver of Fig. 1c and the quadratic-complexity receiver architecture using Synopsys's OptSim™ for a simplex MVM constellation based on symmetric, informationally complete, positive operator-valued measure (SIC-POVM) vectors[5],[6] with $N = 2, 4, 8$ dimensions and $M = 4, 16, 64$ constellation points, respectively.

Fig. 2 shows the symbol error rate (SER) vs. amplified spontaneous emission (ASE) symbol signal-to-noise ratio (SNR) per spatial degree of freedom (SDOF) for both quadratic- and linear-complexity receivers. In the exclusive presence of ASE noise, both receiver architectures show identical performance. For $N = 2$, 4, and 8, the quadratic complexity receiver requires 6, 28, and 120 photodiodes, while the linear complexity receiver requires only 6, 16, and 36 photodiodes to achieve the same performance. Further investigation of the respective receivers' performances with the inclusion of device imperfections, shot noise, and thermal noise is left for future work.

IV. Summary

We designed a novel mode-vector direct-detection receiver architecture that leverages the interdependence of Stokes parameters to achieve linearly-scaling hardware complexity with respect to the number of spatial and polarization degrees of freedom.

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