Robust OAM Multiplexing via Shift-Diversity Matched Filtering under Receiver Misalignment

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Abstract

Orbital angular momentum (OAM) multiplexing has emerged as a promising method to enhance spectrum efficiency in line-of-sight wireless communication links. However, OAM systems are susceptible to receiver misalignment and pointing jitter, which induce modal crosstalk, degrade channel conditioning, and significantly reduce link capacity. Conventional OAM receivers rely on a single matched filter per mode, implemented through conjugate array correlation, inverse spiral phase plates, or phase-shift networks, which works only under perfect coaxial alignment. To address this limitation, we propose a Shift-Diversity Matched Filtering (SDMF) framework that requires no modifications at the transmitter and operates entirely at the receiver. By augmenting each mode's matched filter with a small set of spatially shifted correlators, SDMF ensures that at least one branch remains well aligned with the incident mode under lateral displacement. Linear combining using minimum mean-square error (MMSE) filtering is then applied to exploit spatial diversity and restore mode orthogonality. Under realistic misalignment conditions, SDMF consistently outperforms LG-DFT by preserving channel capacity and reducing both error rates and inter-mode crosstalk, thereby improving overall link robustness.

Index Terms—Orbital Angular Momentum, Uniform Circular Array, Shift Diversity Matched Filtering, Minimum Mean Square Error

Ⅰ. Introduction

OAM multiplexing enables multiple data streams to coexist on the same carrier frequency by exploiting the orthogonality of helical phase modes. Early demonstrations [1], [2] employed a single matched filter per OAM mode, implemented using inverse spiral phase plates, phase-shift networks, or conjugate array correlation. While effective under perfect alignment, these methods are extremely sensitive to lateral shifts, tilt, or pointing jitter, which destroy orthogonality and cause strong inter-mode interference. As a result, channel capacity degrades sharply [3], [4]. A recent study [5] proposed a leakage-based precoding method to enhance OAM capacity by mitigating inter-mode interference, but it focuses on transmitter-side optimization. In contrast, our proposed Shift-Diversity Matched Filtering (SDMF) offers a receiver-only solution. The LG-DFT receiver, which applies DFT weights on a UCA to extract LG OAM modes, offers hardware efficiency but also breaks down rapidly under misalignment. This motivates receiver-only solutions that enhance robustness without requiring transmitter modifications.

Ⅱ. Methodology

We propose Shift-Diversity Matched Filtering (SDMF) to enhance the robustness of OAM receivers. The key idea is to replace the single matched filter per mode with a bank of K shifted correlators, each corresponding to a slightly displaced steering hypothesis. This creates diversity at the receiver, ensuring that at least one correlator branch remains aligned with the actual misaligned field.

To model the baseline OAM system, consider N OAM modes to be transmitted as a symbol vector $S = [S_1, S_2, \dots, S_N]^T$. The received signal at an N_r element circular array can be expressed as

$$r = Hs + n, \qquad (1)$$

where $\mathrm{H} \in \mathbb{C}^{\mathrm{N}_r \times \mathrm{N}}$ contains the steering vectors for each OAM mode and $n \sim CN(0, \sigma^2 I)$ is additive noise.

Under perfect coaxial alignment, OAM vectors satisfy

$$h_\ell^H h_m \approx 0, \quad (\ell \neq m).$$

Thus, a conventional matched filter per mode

$$y\ell = h_\ell^H r$$

Achieves nearly interference-free detection. However, misalignment introduces additional phase tilts, and the distorted steering vector can be approximated as

$$h_\ell(\Delta K_x, \Delta K_y) \approx diag\left(e^{-jk(x_n \Delta K_x + y_n \Delta K_y)}\right) a_\ell, \qquad (2)$$

where ($\Delta K_x, \Delta K_y$) represent displacement-induced phase shifts and a_ℓ is the nominal vector. This breaks orthogonality, leading to crosstalk. To address this, we propose Shift-Diversity Matched Filtering (SDMF), in which each OAM mode ℓ is augmented with K=5 shifted templates defined as

$$w_{\ell,k} = h_\ell(d_k)^*, \quad k = 1, \dots, K,$$

where $d_k \in \{0, \pm 0.30^\circ_x, 0, \pm 0.30^\circ_y\}$ corresponds to small angular tilt hypotheses. The outputs of the correlators are stacked into: $y = W^H r = Gs + n_y$,

with $W = [w_{1,1,\dots,} w_{N,K}]$, $G = W^H H$ and $n_y = W^H n$.

Since at least one branch per mode remains aligned with the misaligned field, useful signal energy is preserved. Finally, the MMSE detector linearly combines the shifted outputs to maximize the desired signal while suppressing interference.

$$\hat{s} = (G^H G + \sigma^2 I)^{-1} G^H y. \qquad (3)$$

The effective mapping is

$$\hat{s} = Bs + \tilde{n}, \quad B = (G^H G + \sigma^2 I)^{-1} G^H G,$$

which shows that when $G^H G$ is well-conditioned, restoring mode orthogonality. Thus, SDMF provides robustness against misalignment by expanding the receive space through multiple shifted correlators and optimally combining them using MMSE detection.

Ⅲ. Performance and Evaluation

The proposed SDMF was compared with the baseline LG-DFT using a 16×16 UCA, transmitting four independent data streams corresponding to two OAM modes (ℓ = 0,1) multiplexed across two orthogonal channels. Misalignment was modeled as Gaussian lateral displacement (σ = 0, $0.4 w_{eff}$, $0.8 w_{eff}$). The initial results show that SDMF achieves a lower crosstalk index and better-conditioned channels than LG-DFT. As illustrated in Fig. 1, the crosstalk index

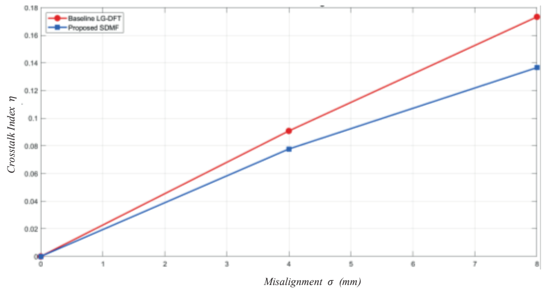

Fig. 1. Crosstalk Index vs Misalignment

versus misalignment curves further confirm that SDMF effectively suppresses inter-mode interference, restoring mode orthogonality and improving robustness without transmitter modification.

Ⅳ. Conclusion

We propose an SDMF receiver to mitigate misalignment sensitivity in OAM-based systems. By augmenting each mode with multiple shifted correlators and combining them via MMSE detection, SDMF effectively mitigates modal crosstalk and restores approximate orthogonality without any transmitter modification. Simulations demonstrate that SDMF achieves better conditioning, reduced crosstalk, and higher modal purity compared to LG-DFT, providing a robust and practical solution for OAM-based wireless links.

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