EE367 Project Proposal: Fundamental Tradeoffs in Space–Time Multiplexed Computational Imaging

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Motivation

Computational imaging systems expand optical design beyond traditional image formation by encoding measurements that are later recovered algorithmically. In recent years, spatial multiplexing has emerged as a powerful tool for increasing compactness and enabling compressive sensing. Information-theoretic analyses have shown that the effectiveness of spatial multiplexing depends critically on object properties such as sparsity and on noise characteristics. However, these studies focus on static spatial encoders and do not consider the additional degrees of freedom available through temporal modulation.

Modern programmable optical platforms — including spatial light modulators, coded shutters, and dynamically reconfigurable phase masks — allow optical encoding patterns to vary during a single exposure. This introduces a new design dimension: space–time multiplexing. Temporal coding has been used for applications such as compressive video and motion deblurring, but its fundamental impact on information capture remains poorly understood. In particular, under fixed exposure time and fixed photon budget, it is unclear whether temporal multiplexing increases the recoverable information about a scene, and under what object or noise regimes it provides benefit.

Understanding these tradeoffs is essential for guiding the design of next-generation programmable optical systems. By extending information-theoretic analysis from static spatial encoders to time-varying optical operators, this project seeks to establish principled rules for when and how temporal coding improves computational imaging performance.

Related work

Recent work has established mutual information as a powerful, decoder-independent metric for analyzing and designing computational imaging systems [1]. Information-theoretic analysis of optical systems traces back to Shannon's communication framework and has been applied to incoherent imaging by Ashok and Neifeld, who quantified information transfer under noise and system constraints. More recently, mutual-information-driven design has been used to analyze and optimize spatially multiplexed lensless imaging systems, revealing that optimal spatial coding depends on object sparsity and measurement noise. In parallel, multiplexing tradeoffs in computational imaging have been studied in the context of compressive sensing and coded aperture systems, emphasizing the interplay between signal priors, noise, and measurement design [2]. Temporal coding has also been explored through coded exposure photography and compressive temporal imaging, where time-varying modulation enables recovery of high-speed dynamics from limited measurements (eg: flutter shutter [3]. However, these approaches are typically evaluated using reconstruction performance rather than decoder-independent information metrics. A unified information-theoretic analysis of space–time multiplexed imaging under fixed exposure constraints has not yet been systematically developed, motivating the present study.

Project overview

This project investigates how temporal modulation affects information capture in computational imaging systems. While prior work has analyzed static spatial multiplexing, we extend the forward model to include time-varying optical encoders and study how space–time multiplexing influences mutual information under fixed exposure constraints.

We model imaging as a time-dependent convolution process:

$$y_t = (o * h_t) + n_t, \qquad t = 1, ..., T \tag{1}$$

where h_t represents a temporally modulated point spread function and the total photon budget is fixed across all temporal codes. Performance will be evaluated using mutual information as a decoder-independent metric.

The core goal is to determine whether increasing the number of temporal codes T improves information capture, and under what object regimes (dense vs. sparse, static vs. dynamic scenes) temporal multiplexing provides measurable benefit. All experiments will be simulation-based and will focus on identifying qualitative trends and tradeoffs rather than full encoder optimization.

Milestones

- Week 1:
  - Implement static spatial imaging model (T = 1).
  - Simulate two object classes: 1) Dense natural images 2) Sparse point-source objects
  - Implement mutual information estimation
  - Validate baseline behavior versus object sparsity.
- Week 2:
  - Extend model to time-varying encoder h_t
  - Test results of different random temporal codes and try different numbers of temporal codes (eg: $T = 1, 2, 3...6$)
  - Compute mutual information vs. T for static scenes.
- Week 3:
  - Simulate simple temporally sparse scenes (dynamic scenes)
  - Compare static vs. dynamic scene results
  - Evaluate mutual information scaling with temporal multiplexing

References

[1] L. A. Kabuli, H. Pinkard, E. Markley, C. S. Hung, and L. Waller, "Designing lensless imaging systems to maximize information capture," *Optica*, vol. 13, no. 2, pp. 227–235, Feb 2026.

[2] K. Mitra, O. S. Cossairt, and A. Veeraraghavan, "A framework for analysis of computational imaging systems: Role of signal prior, sensor noise and multiplexing," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 36, no. 10, pp. 1909–1921, 2014.

[3] R. Raskar, A. Agrawal, and J. Tumblin, "Coded exposure photography: motion deblurring using fluttered shutter," in *ACM SIGGRAPH 2006 Papers*, ser. SIGGRAPH '06. New York, NY, USA: Association for Computing Machinery, 2006, p. 795–804. [Online]. Available: https://doi.org/10.1145/1179352.1141957