Biologically Inspired Sparse Event-Based Communication and Decoding of Spatiotemporal Stimuli

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1 Introduction

Sensory systems encode high-dimensional, continuous inputs under constraints of bandwidth, energy, and delay, posing a coding challenge: how to transmit information efficiently while preserving spatiotemporal structure. We leverage principles of sensory organization—labeled lines, receptive fields, and dual temporal pathways—to design a bio-inspired, event-based scheme that reconstructs spatiotemporal stimuli from sparse spikes. Using the tactile system as a model [1], we simulate Slowly Adapting (SA) and Rapidly Adapting (RA) neurons that encode sustained and transient components of a dynamic pressure stimulus. Both populations sample a two-dimensional receptor grid through Gaussian-weighted, overlapping receptive fields, forming a labeled-line architecture in which each neuron carries a unique, known spatial signature. SA neurons have smaller, sparser receptive fields with less overlap, while RA neurons have larger, denser receptive fields with higher overlap. Together with their distinct temporal dynamics, SA and RA neurons enable robust, efficient encoding across diverse stimuli.

Our proposed pipeline has three stages: (1) spatial compression via fixed, sparse innervation, (2) spiking for bandwidth efficiency and attention, and (3) attention-modulated Kalman filter for optimal localized reconstruction. This event-based representation provides key advantages: bandwidth scales with active neurons rather than total sensor count, and sparsity enables reconstructing only active locations and times.

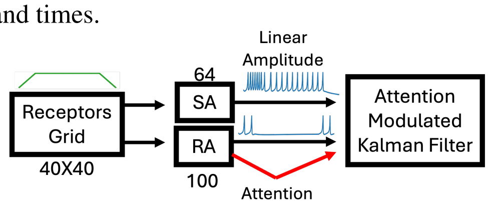

Figure 1: Framework.

2 Proposed Framework

Encoding: Our framework extends the tactile encoding model of Parvizi-Fard et al. [2]. Each simulated sensory neuron samples a two-dimensional receptor grid through a Gaussian-weighted receptive field. Randomized weights produce heterogeneous, overlapping receptive fields that preserve spatial coverage and diversity. SA and RA populations apply complementary temporal filters for sustained and transient components. Filtered inputs pass through Izhikevich neuron models to generate sparse spikes. Although receptive fields are well established in neuroscience, their application to sensor communication has not been widely studied. Barranca et al. [3] explored receptive fields to reconstruct stationary images using compressed sensing. Their approach was limited to stationary images, did not exploit population dynamics, and relied on computationally expensive reconstruction.

Decoding: We extend this work by leveraging neuron dynamics for high compression, accurate reconstruction of dynamical stimuli, and real-time decoding with low computational cost. We use spatial and temporal priors to stabilize reconstruction from sparse, overlapping receptive fields. SA neurons continuously measure pressure amplitude (firing rate $\propto$ intensity), enabling reconstruction of slowly varying stimuli. RA neurons detect and encode rate of change, providing fine-grained localization and triggering event-based attention. By modulating reconstruction locally where RA neurons fire, we achieve higher spatial resolution and reconstruct only active regions. RA activation dynamically adjusts the Kalman filter: measurement noise (R) is reduced for RA and increased for SA locally, prioritizing change detection, while process noise (Q) is elevated to permit rapid state changes. Combining SA and RA populations minimizes spike count while enabling localized processing across stimulus regimes. By restricting reconstruction to regions where RA neurons fire, computational complexity scales with active area rather than total grid size, enabling generalization to arbitrarily large sensor arrays. We propose an event-based SA/RA attention scheme over structured receptive fields that enables spatial compression and targeted reconstruction from sparse spikes. This strategy can be generalized to other sensor arrays and modalities by modifying priors and hidden states without altering the core receptive-field and dynamics framework.

References

[1] B. P. Delhaye et al., "Neural Basis of Touch and Proprioception in Primate Cortex," *Compr. Physiol.*, vol. 8, no. 4, pp. 1575–1602, 2018.

[2] A. Parvizi-Fard et al., "Functional spiking neuronal model for tactile perception," *J. Neurophysiol.*, vol. 126, pp. 1385–1397, 2021.

[3] J. C. Barranca et al., "Sparsity and compressed coding in sensory systems," *PLoS Comput. Biol.*, vol. 10, no. 8, e1003793, 2014.

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