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# Image Restoration Using Optoelectronic Coherent Ising Machine

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**Abstract:** We propose an optoelectronic Coherent Ising Machine implemented using off-the-shelf optical telecommunications devices for image denoising for the first time. Our hardware implementation yields clean images with a pixel error rate of 3%.

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## 1. Introduction

The information era witnessed the mushrooming of the number and quality of images taken and shared every minute. The images freeze in time various social and economic events serving as important memories. Images are crucial in scientific settings such as astronomy (telescopes) and biomedical diagnoses (microscopes, x-rays, MRIs). In all domains, there is an ever-increasing need for cleaner images that are pleasant to the viewers or preserve the detailed information necessary for subsequent processing. Unfortunately, imperfections in the optical sensors, transmission channels, and storage techniques lead to the degradation of the captured images. To improve the quality of images impacted by these distortions there is a need for various methods and techniques [1].

Noise is the prevalent degradation for most images contaminating important details that could be indispensable for diagnosis or discovery. Knowing this, many efforts are directed toward finding image-denoising techniques. Some exploit the fact that noise is a high-frequency addition to images and propose filtering [2]. However, many important details such as edges and textures are also high-frequency components hence filtering results in blurred images. Others propose Convolutional Neural Networks (CNNs) [3]. CNNs are powerful but have high complexity with heavy resource requirements. In this work, we propose a hardware optoelectronic Coherent Ising Machine (CIM) for image denoising. Our implementation benefits from the high speed and efficiency of optical telecommunication systems and offers promising results.

## 2. The proposed model for image denoising

Ising Machines are autonomous brain-like networks of simple elements with properties that can be leveraged for solving Combinatorial Optimization problems [4]. They have been found useful to search the ground state of an Ising Hamiltonian of the Ising model named after *Ernst Ising*, imitating the ferromagnetic properties of magnetic moments of metals at different temperatures.

For simplicity, let us model a hidden black and white image by the spin configuration  $\sigma = (\sigma_s)_{s \in \Omega}$ , where  $\Omega$  denotes the pixel lattice. Let the observed noisy image be the hidden image altered by salt and pepper noise with spin error probability  $p = 20\%$ . Then, maximum a posteriori restoration of  $\sigma$  consists in minimizing an Ising Hamiltonian of the form

$$E(\sigma) = -\frac{1}{2} \sum_{(s,t) \in \mathcal{N}} J_{s,t} \sigma_s \sigma_t - \sum_{s \in \Omega} b_s \sigma_s, \quad (1)$$

whose first (resp. second) term accounts for interactions between adjacent pixels (resp. the likelihood of each individual spin). The matrix  $\mathbf{J}$  defines the spin ferromagnetic interactions ( $J_{s,t} = 1$ ) with end-round boundary conditions. The bias term  $b$  represents the raster scan of the noisy black and white image to be cleaned.

We implement a generalized Hopfield network similar to [5] with one internal neuron per pixel to minimize (1), both digitally and with the hardware depicted in Fig. 1. The nonlinear activation function, implemented in the optical domain by a standard Mach-Zehnder Modulator (MZM) followed by a photodiode, is applied one at a time to each internal neuron using time division multiplexing. The feedback strength affecting each neuron's evolution is implemented in a PC and converted back to the optical domain by an Arbitrary Waveform Generator (AWG).

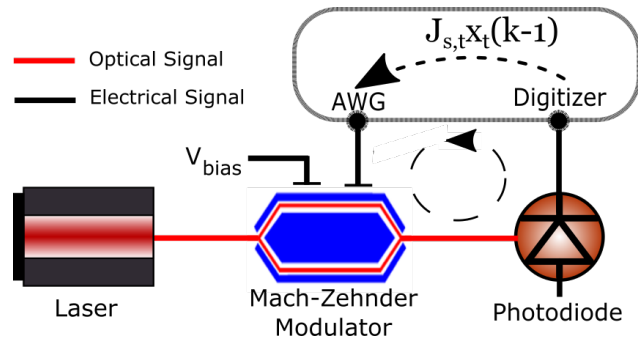


Fig. 1: The optoelectronic CIM setup using off-the-shelf components intended for optical telecommunications. The internal neuron of the Hopfield network for pixel  $t$  at iteration  $k$  is denoted by  $x_t(k)$ .

### 3. Results

After proper calibrations, we introduce the noisy image similar to that of Fig. 2a and after about 10 iterations we obtain the cleaner images shown in Fig. 2b (resp. 2c) for the optoelectronic (resp. digital) CIMs. The resultant images have pixel errors of 3% and 2.3% respectively. By defining success as attaining at most 98% of the ground state energy, which is approximately  $E_{ground}(\sigma) = -5500$  for these images, the success probability of the optoelectronic and digital CIMs are 86.75% and 89% respectively.

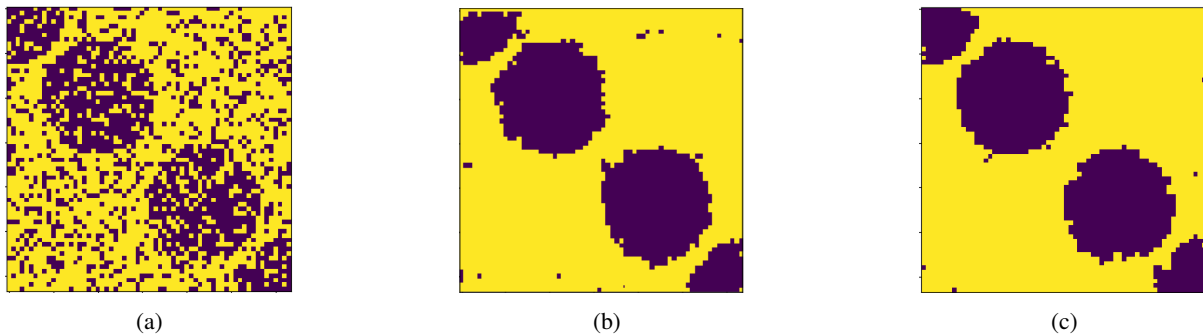


Fig. 2: 64-by-64-pixel Images showing the initial noisy (a) and final cleaned images for the hardware (b) and digital (c) CIMs. The bright yellow pixels are for spin-up and the dark purple pixels are for spin-down.

### 4. Conclusion

We have demonstrated the potential of optics in image restoration in the form of Coherent Ising Machines. Our experiments explore the numerical and optoelectronic hardware implementation of CIMs. Given images impacted heavily by noise, our proposal can restore the image to cleaner versions in a few iterations. Although with a slightly higher pixel error rate and lower convergence probability, in the spirit of compromise, our hardware implementation of CIM has the potential for faster and more energy-efficient CIMs. In the future, we aim to extend this work by studying the speed and energy gains by the experimental CIM to underline the performance-cost trade-offs associated with using the hardware CIM over the digital one.

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