

No free lunch in analog Ising solvers: memory non-idealities, trapping and mitigation

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Analog combinatorial optimization engines, such as Ising machines and Hopfield networks, can solve hard problems efficiently by exploiting physical dynamics that evolve toward low-energy states. Their performance, however, strongly depends on how accurately coupling weights are realized in hardware. In practical analog implementations, limited programming precision and device variability distort these couplings, alter the energy landscape, and increasingly degrade performance as problem size grows.

In this work, we quantify the precision required to solve 3-SAT and Max-3-SAT problems in analog solvers and explain the mechanisms behind performance loss at low precision. We model coupling imperfections as additive Gaussian perturbations on nonzero weights and define an **effective bit resolution (EBR)** by equating the measured RMS weight noise to the quantization noise of an ideal uniform quantizer. This bridges analog noise to digital bit precision, consistent with standard effective-number-of-bits (ENOB) concepts [1]. This provides a direct digital-equivalent measure of analog programming accuracy. Measurements from a 64×64 CMOS-integrated memristive crossbar confirm near-Gaussian programming statistics and show that lower EBR increases wrong-flip events, which are critical to solver dynamics.

Our results show two distinct degradation regimes. At moderate error levels, the true optimum often remains unchanged, but local minima deepen and parasitic low-energy states become more attractive, increasing trapping and sharply worsening time-to-solution and energy-to-solution. At higher error levels, the original ground state is destabilized, spurious optima emerge, and solver success probability collapses.

We further show that robustness strongly depends on the chosen problem formulation. For the same higher-order optimization task, a native PUBO mapping is both faster [2] and more resilient to programming errors than its quadratized QUBO counterpart, requiring significantly lower effective precision to achieve the same target performance. We also evaluate mitigation strategies, including noise-aware hyperparameter tuning, column replication with majority voting, and column-normalized weight assignment, all of which reduce the required precision with limited overhead.

Overall, this work links device-level coupling errors to system-level failure modes and establishes quantitative precision requirements for analog Ising and Hopfield solvers, providing practical guidance for precision-aware algorithm–hardware co-design.

[1] “IEEE Standard for Digitizing Waveform Recorders,” *IEEE Std 1057-2017 (Revision of IEEE Std 1057-2007)*, p. 1, 2018, doi: 10.1109/IEEESTD.2018.8291741.

[2] M. Hizzani *et al.*, (*ISCAS*), doi: 10.1109/ISCAS58744.2024.10558658.