DOIM50: A 50-Spin Fully Connected Oscillator Ising Machine IC for MU-MIMO detection

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Abstract—Networks of coupled nonlinear oscillators have garnered significant attention for their ability to perform computation through synchronization and phase dynamics. In particular, Oscillator Ising Machines (OIMs) utilize coupled nonlinear oscillators to solve combinatorial optimization problems by exploiting their intrinsic nonlinear dynamics. This paper presents a custom-fabricated integrated circuit (IC) implementing a 50-spin OIM, demonstrating its ability to solve real-world optimization problems. While prior research has largely focused on simulated OIMs, our fabricated IC provides experimental validation of oscillator-based computation for multi-user multiple-input multiple-output (MU-MIMO) detection.

1. Introduction

Coupled oscillator systems naturally exhibit synchronization, a phenomenon that has been widely studied in physics and engineering. Over the past decade, researchers have demonstrated that these networks can be engineered for computational purposes, particularly in solving complex combinatorial optimization problems (COPs). One such approach, known as the Oscillator Ising Machine (OIM), leverages the phase dynamics of coupled nonlinear oscillators to minimize an associated "energy" function. Amongst other alternatives [1, 2], OIMs stand out for their compactness and strong performance across a wide range of optimization problems [3, 4, 5]. While simulations of OIMs have shown considerable promise, experimental implementations are still in the early stages of development. In this work, we present a custom-fabricated integrated circuit (IC) implementing a 50-spin OIM, demonstrating its capability to solve an important real-world problem in communications—multi-user multiple-input multiple-output (MU-MIMO) detection.

The ability of OIMs to solve COPs stems from the connection to the Ising model, a fundamental statistical physics formulation. The Ising model consists of discrete variables s_i (spins) that take binary values ± 1. The system's energy is described by the Ising Hamiltonian:

$$H \triangleq -\sum_{1\leq i<j\leq n} J_{ij} \cdot s_i \cdot s_j - \sum_{i=1}^{n} h_i \cdot s_i, \qquad (1)$$

where n is the number of spins; $\{J_{ij}\}$ and $\{h_i\}$ are real coefficients. To accommodate the second summation term ("magnetic field" term) as part of the first summation term, an extra spin (s_{n+1}) is introduced with value fixed at "+1". We term this additional spin the REF spin. With the inclusion of the REF spin, the linear terms h_i can be incorporated into the pairwise terms by defining $J_{i,n+1} = h_i$.

Finding the ground state[†] of the Ising model is a classic example of a COP. COPs are fundamental to fields such as logistics, finance, and cryptography. These problems are generally either NP-hard or NP-complete, meaning that no classical algorithm can solve them in polynomial time. As a result, finding solutions is computationally expensive, often requiring exponential time. All of Karp's 21 NP-complete COPs can be mapped to Ising by assigning appropriate values to the coefficients ($\{J_{ij}\}$) [6]. The generality of the Ising formulation has spurred significant interest in hardware solvers—called Ising machines—that leverage physical dynamics to find near-optimal solutions.

In this work, we address real-world MU-MIMO optimization problems using a custom designed and fabricated dense OIM IC, `DOIM50`. On a set of 250 64x16 QPSK[‡] MU-MIMO problems provided by Nokia Bell Labs, our chip demonstrates very good performance under realistic signal-to-noise ratio (SNR) and channel conditions. To our knowledge, these are the first successful results demonstrated on an Ising machine IC. Without post-processing,

Author contributions: VPSS wrote the paper, contributed to the schematics and layouts of oscillator-conditioning circuits and phase detectors, designed the PCBs, brought up and debugged the system, set up and executed testing, ran MIMO problems, and collected/analyzed chip data. SS worked on the chip design and tapeout, including architecture conceptualization, schematics and layouts for varactor-based oscillators and couplers, top-level integration, and aspects of testing—thus building the core around which this work is based. GDG drafted an early version of the manuscript and contributed to system bring-up (including FPGA code), testing, MIMO runs, and data collection/analysis. TJ and JHH worked on the on-chip digital controller. RM and JR provided overall guidance.

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[†]Ground state—a state that achieves the minimum Hamiltonian.

[‡]Quadrature Phase Shift Keying, a common modulation scheme used in MIMO systems

DOIM50 achieved zero bit errors for 53% of the problems, with only one bit error in the remaining problems. A single pass of computationally inexpensive 1-bit flip post-processing further enhanced the solvability to 100%, solving all the problems with zero bit errors. These results underscore DOIM50's capability to effectively solve real-world complex optimization tasks.

The rest of the paper is organized as follows: Sec. 2 provides the necessary background on OIMs and introduces the MIMO detection problem. Sec. 3.1 details the IC hardware architecture and its components. In Sec. 4, we present the experimental results. Finally, Sec. 5 concludes the paper with a discussion of key findings.

2. Background

2.1. Oscillator Ising Machines

Oscillators are systems that produce periodic oscillations and are characterized by a natural frequency at which they oscillate when undisturbed. When multiple oscillators are coupled in a network, they can be harnessed to solve COPs [3]. Such coupled oscillator systems naturally evolve toward a low "energy" state due to a phenomenon called injection locking, a nonlinear synchronization effect that governs the dynamics of a perturbed oscillator.

2.1.1. Injection Locking

When an oscillator with a natural frequency f_0 is perturbed by a small periodic signal oscillating at a frequency of $f_1 \approx f_0$, the oscillator can adjust its behavior to synchronize with the perturbation signal [7]. This phenomenon is called injection locking, or more precisely, fundamental harmonic injection locking (FHIL). The phase response to the perturbation can be accurately predicted using the Generalized Adler's model [7], which governs the dynamics of the oscillator's phase under periodic inputs. Following this, FHIL ensures the oscillator oscillates at the same frequency (f_1) and maintains a fixed phase relationship with the perturbation signal. Sub-harmonic injection locking (SHIL) can occur when an oscillator is perturbed by a small periodic signal oscillating at a frequency of f_2, close to twice the oscillator's natural frequency *i.e.*, $f_2 \approx 2 \cdot f_0$. Under SHIL, the oscillator synchronizes with the perturbation signal and starts oscillating at half the perturbation frequency, *i.e.*, $\frac{f_2}{2} \approx f_0$. SHIL leads to bistable phase behavior, where the two stable phase states are separated by 180°. As a result, the oscillator effectively acts as a phase-based binary latch, capable of storing one bit of information [8].

2.1.2. Coupled Oscillator Dynamics

It has been shown in [9] that the dynamics of coupled oscillators with SHIL inputs are abstracted using the generalized Adler model. For simplicity, when the oscillations are assumed to be sinusoidal, and with some other approximations, the system dynamics can be modeled using the Kuramoto model, which is given by,

$$\begin{aligned}\frac{d}{dt}\phi_i(t) = -K_c \sum_j J_{ij} \cdot \sin(\phi_i - \phi_j) \\ - K_s \cdot \sin(2 \cdot \phi_i) + K_n \cdot \xi_i(t).\end{aligned} \tag{2}$$

In (2), ϕ_i represents the phase of the ith oscillator, and J_{ij} represents the coupling weights between oscillators. The system dynamics are controlled by several key parameters: K_c represents the coupling strength between oscillators; K_s quantifies the strength of the SHIL signal; and K_n represents the standard deviation of the noise term $\xi_i(t)$, modeled as Gaussian white noise with zero mean.

SHIL ensures the oscillator phases stabilize to discrete values in the steady state, effectively binarizing the phases, which encode spin states. A 0° phase corresponds to spin-up (+1) and 180° corresponds to spin-down (-1).

2.1.3. Lyapunov Function

As worked out in [9], a global Lyapunov function can be deduced for the coupled oscillator system described in (2). Consider the scalar function $E(\phi(t))$:

$$\begin{aligned}E(\phi(t)) = -K \sum_{i,j,i\neq j} J_{ij} \cos(\phi_i(t) - \phi_j(t)) \\ - K_s \sum_i \cos(2\phi_i(t)).\end{aligned} \tag{3}$$

Following the system dynamics, we can easily show that:

$$\frac{\partial E(\phi(t))}{\partial t} = -2 \sum_k \left(\frac{d\phi_k(t)}{dt}\right)^2 \leq 0. \tag{4}$$

Implying that $E(\phi(t))$ decreases over time. Since the phases are either 0° or 180° in the steady state, we have $\cos(\phi_i - \phi_j) = s_i s_j$. Thus, the Lyapunov function $E(\phi(t))$ reduces to

$$E(\mathbf{s}) = -K \sum_{i,j,i\neq j} J_{ij} s_i s_j - n \cdot K_s, \tag{5}$$

where n is the number of oscillators. By choosing K = 1/2, we can make (5) equivalent to Ising Hamiltonian in (1) with a constant offset. This shows that the system dynamics lower the Lyapunov function and in-turn the Ising Hamiltonian over time, and hence **the coupled oscillator network qualifies as an Ising machine, and we refer this system as Oscillator Ising Machine**.

2.2. MU-MIMO Detection

Modern wireless communication systems, such as 5G, Wi-Fi, and massive IoT networks, rely on MIMO technology to enhance capacity and reliability using multiple antennas at both the transmitter and receiver. A key challenge in MIMO communication is detection: since all transmitted signals share the same wireless channel, each receiver antenna captures a superposition of signals, making it difficult to recover the originally sent signals.

MIMO detection aims to reconstruct the originally-sent transmitted (discrete) symbols from the received (real-valued) signals, which are corrupted by noise. The problem [10] is to recover $x \in \{-1, 1\}^n$ from an observation of the form

$$y = H \cdot x + e, \quad y \in \mathbb{R}^n, \tag{6}$$

where $H \in \mathbb{R}^{m\times n}$ is a known channel matrix and $e \in \mathbb{R}^m$ represents noise. The detection task is commonly formulated as a maximum likelihood estimation problem, which is known to be NP-hard, making exact solutions computationally expensive.

$$\text{The goal: } \min_{x\in\{-1,1\}^n} \|y - H \cdot x\|. \tag{7}$$

Notably, MIMO detection can be mapped to an Ising problem without any increase in problem size [11], enabling efficient solution using Ising machines. The detection problem becomes more challenging for large-scale multi-user MIMO (MU-MIMO) systems.

3. DOIM50

To solve MU-MIMO detection problems using our fabricated IC—`DOIM50`—we begin by mapping each MIMO instance to an equivalent Ising problem [11]. The corresponding Ising weights are then programmed onto the chip via a UART* interface. Next, we calibrate the oscillator frequencies to ensure that all oscillators operate within each other's injection locking range. Once calibration is complete, we start the oscillator network to let the system evolve toward a solution. Finally, we directly read out the spin configuration from the chip.

3.1. Architecture

Fig. 1 illustrates the architecture of the fabricated chip, DOIM50. The system comprises three main components: the oscillator array, a varactor (variable capacitor)-based crossbar, and digital logic for programming coupling weights and interfacing with the external world.

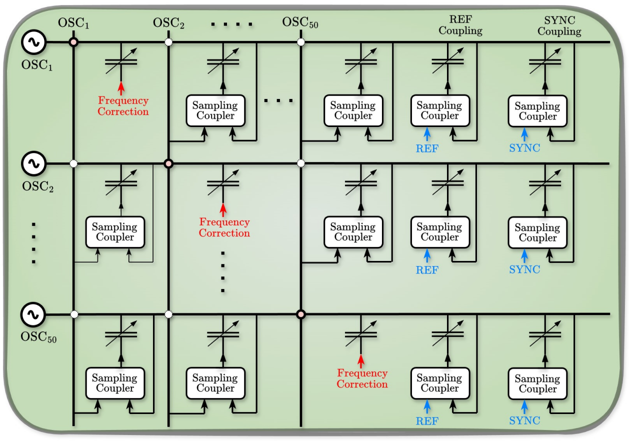

Figure 1: Chip crossbar architecture.Varactors corresponding to the frequency calibration are placed at the diagonals.

3.1.1. Oscillator Array

Spins in the Ising model are represented using three-stage fully differential analog oscillators (Fig. 2), where the phase of each oscillator encodes the spin state. These oscillators are designed to operate at a nominal frequency of 4 MHz. Since the oscillators are implemented using analog circuits, their output amplitude is relatively small. However, the couplers require a rail-to-rail square waveform, as the oscillator signals serve as inputs to a digital latch. To meet this requirement, the signals are conditioned as shown in Fig. 2. The low-amplitude differential output is first amplified using a differential amplifier, then passed through a divide-by-2 circuit based on CML latches to ensure a 50% duty cycle with sharp transitions. Finally, the signal is further amplified and buffered to produce a rail-to-rail output for robust distribution to all couplers.

*Universal Asynchronous Receiver-Transmitter, a common serial communication protocol for low-overhead device interfacing.

This buffered, divided-by-2 signal effectively represents the oscillator output, and this 2 MHz signal is referenced to an external signal (REF) of the same frequency. A spin state of +1 corresponds to the oscillator being in phase with the REF signal, which is always assumed to represent a spin of +1, as described in Sec. 2.1.2. Conversely, a spin state of -1 corresponds to a 180° phase shift with the REF signal.

3.1.2. Coupling Mechanism

The varactor-based coupling scheme synchronizes oscillators by dynamically adjusting their frequencies. To modify the frequency of a particular oscillator (the "target oscillator"), the scheme monitors the timing of rising edges from other oscillators (referred to as "incoming oscillators") relative to the target. In the case of positive coupling, if the rising edges of incoming signals arrive earlier than those of the target oscillator, the coupling mechanism speeds up the target oscillator. Conversely, if they arrive later, it slows down the target oscillator. The behavior is reversed in the case of negative coupling. This feedback ensures that, at steady state, all oscillators "lock" to each other—either in-phase or out-of-phase—while operating at approximately the same frequency.

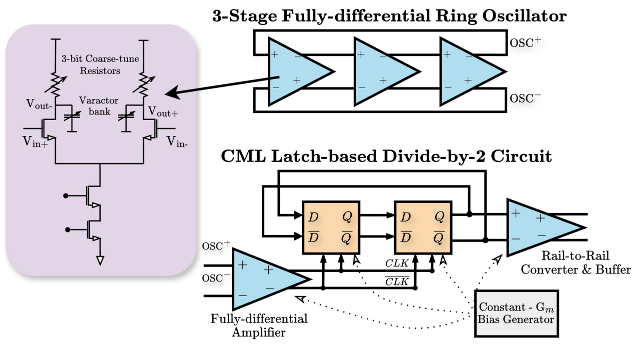

Figure 2: Three-stage fully differential oscillator featuring a 3-bit resistor bank for coarse frequency tuning, along with auxiliary circuits for generating an accurate 50% duty cycle signal, with rail-to-rail conversion and buffering amplifiers.

This adjustment is implemented in hardware using a sampling coupler [12], which consists of two latches that detect the relative timing between the target and incoming oscillators and apply either VDD or GND to the "bottom plates" of corresponding digitally controlled varactors. Each oscillator connects to 52 varactor banks: 49 for oscillator-to-oscillator coupling, one for the reference (REF), one for synchronization (SHIL), and one for fine frequency tuning. Each varactor bank supports 8-bit digital control and a sign bit, enabling both positive and negative coupling. The sampling coupler selectively overrides these defaults to speed up or slow down the oscillator, based on the coupling polarity and the relative arrival time of incoming edges, as described in this work [12]. Simulations using the PPV model [13] confirm that this coupling scheme solves Ising problems effectively.

3.2. Frequency Calibration

Injection locking is essential for the correct operation of the system, as it enables the oscillators to synchronize and collectively solve optimization problems. However, due to process, voltage, and temperature (PVT) variations, as well as component mismatches, the natural frequencies of the oscillators may differ at power-up. To ensure reliable injection locking, all oscillators must operate within each other's locking range. To address this, `DOIM50` reserves specific varactor banks in each oscillator for fine frequency control. One of the 52 varactor banks is dedicated to calibration, and five additional banks—originally intended for coupling with oscillators 46–50—can be repurposed to extend the tunable frequency range. The effectiveness of the calibration scheme is apparent from Fig. 3.

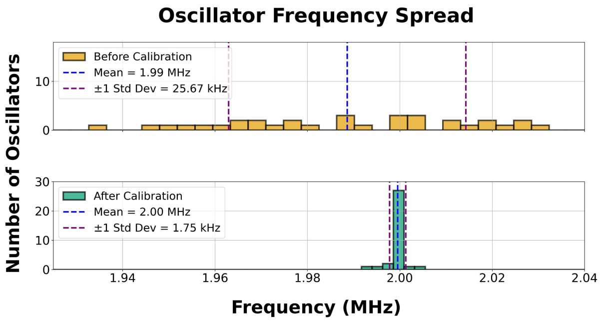

Figure 3: Frequency spread before and after calibration, demonstrating that post-calibration, all oscillators oscillate close to the nominal frequency (2MHz).

4. Results — Solving MU-MIMO Problems

Fig. 4 shows the testing setup used for this evaluation. We evaluated the chip using 250 instances of 64 × 16 QPSK MU-MIMO detection problems provided by Nokia Bell Labs. Designed with an SNR of 9 and incorporating channel correlations [14, 10], these benchmarks represent realistic and challenging wireless communication scenarios. We executed each problem 30 times and compared

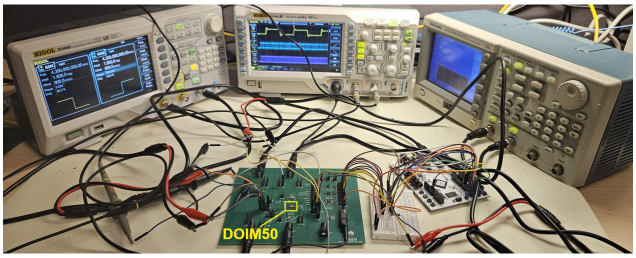

Figure 4: DOIM50 testing setup.

the resulting spin configurations to ground-truth solutions to compute bit error rates. If at least one of the 30 runs produced a zero-bit-error solution, we marked the problem as correctly solved. We defined the success rate for each problem as the fraction of runs that yielded a correct solution. Fig. 5 shows a histogram of the success rates for all 250 problems. Without any post-processing `DOIM50` achieves zero bit errors (non-zero success rate in Fig. 5) in 53% of the problems and exactly one bit error in the remaining 47%. After applying a simple and computationally cheap 1-bit-flip post-processing step to the extracted spin configurations, we achieve a near-100% success rate across all problems. These results remain consistent across independent trials, demonstrating the system's robustness and effectiveness.

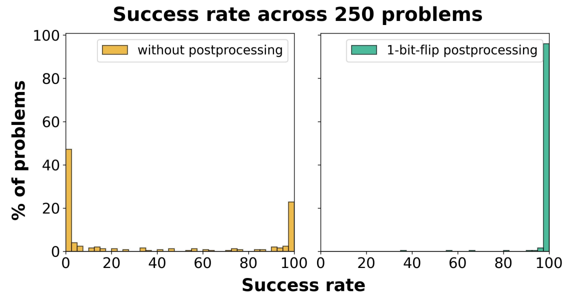

Figure 5: Histogram of success rates.

5. Conclusion

We have presented `DOIM50`, a fabricated 50-oscillator analog Ising machine capable of solving real-world optimization problems. Through frequency calibration and programmable coupling, `DOIM50` achieves robust and reproducible performance on challenging MU-MIMO detection tasks. It solves all 250 benchmark problems with near-100% success after simple post-processing, marking a significant step forward for practical analog computing. These results highlight the potential of oscillator-based Ising machines as scalable and energy-efficient solvers for practical applications.

Acknowledgments

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