出力層のみを対象としたアナログ風エンコーディングとノイズ注入のベンチマーク

Analog NN Benchmarking

Abstract

本報告は、**出力層のみ**をノイズでモデル化した 5 種類の MLP 分類器（デジタル基準、乗算ノイズ「Amplitude」、乗算ノイズを伴う学習、位相コサイン重み、位相ノイズを伴う学習）を、5 つのデータセット（MNIST, KMNIST, EMNIST Letters, CIFAR-10 平坦化, Fashion-MNIST）で比較する。各データセットの固定ノイズグリッド上で精度を評価し、1 データセット当たりの平均精度と簡易的な頑健性指標（ノイズ曲線の最大値–最小値）をまとめる。単一シードかつ各 σ につき 1 回の重み摂動という前提では、乗算ノイズを伴う学習（amplitude_noiseaware）はデジタル基準にほぼ一致する平均精度（0.8329 vs 0.8359）を保ちつつ、変動幅を縮める。位相モデルはノイズなし学習では不安定だが、ノイズを伴う学習で大幅に改善する（0.6156 → 0.8002）。**本研究は出力層のみをアナログ風に扱う限定的スコープである**ことを強調する。

1　はじめに

アナログ／アナログ風アクセラレータは低レイテンシと省電力が期待される一方、ノイズやばらつきに弱い。本稿では**出力層のみ**をアナログ風エンコード（乗算ノイズ、位相コサイン重み）し、デジタル MLP 基準と比較する。主眼は (1) デジタル精度にどこまで近づくか、(2) ノイズを伴う学習の効果、(3) データセット難易度による傾向差である。

2　モデルとノイズ注入

スコープは**出力層のみ**のノイズモデルであり、中間層はデジタルのまま。非理想性は重みごと独立のノイズとして推論時に注入し、ノイズを伴う学習では学習時にも注入する。

- **Digital**: 通常の MLP。出力層の線形写像でロジットを得る。
- **Amplitude（乗算ゲインノイズ）**:

$$W_{\text{noisy}} = W \odot (1+\epsilon), \quad \epsilon \sim \mathcal{N}(0, \sigma_{\text{amp}}^2).$$

- **Amplitude_noiseaware**: 上記を学習時にも注入し、`train_noise_list` から σ をサンプル。
- **Phase（コサイン重み）**:

$$\begin{aligned} &\Theta \in \mathbb{R}^{d\times C}, \quad \epsilon \sim \mathcal{N}(0, \sigma_{\text{phase}}^2) \text{ (要素ごと)}, \\ &W = \cos(\Theta), \quad W_{\text{noisy}} = \cos(\Theta+\epsilon), \quad \text{logits} = x^\top W_{\text{noisy}} + b. \end{aligned}$$

- **Phase_noiseaware**: 学習時に `train_noise_list` から σ をサンプルして注入。

損失はクロスエントロピー。最適化は Adam（データセット別の lr/epoch は `config.yml`）。バッチ 128、シード 42。デバイス選択は mps → cuda → cpu。

3 データセット

MNIST, KMNIST, EMNIST Letters, CIFAR-10（32×32×3 を平坦化）, Fashion-MNIST。各データセットの `hidden_dims` や学習率は `config.yml` に記載。

4 実験設定

- **ノイズ掃引**: `config.yml` の `noise_std` リストを推論時に適用。
- **ノイズを伴う学習**: `train_noise_list` から σ を 1 ステップごとにサンプル。
- **1 回サンプル/** σ: 各 σ で重みノイズ ϵ を 1 回だけサンプルし、そのままテスト全体を評価。
- **分割**: 学習用に訓練データの 80%、テストは公式テストセット。
- **前処理**: ToTensor + 正規化 + 平坦化。
- **デバイス**: 自動選択（mps → cuda → cpu）。MPS/CUDA は厳密決定性を保証しないため、再現性重視なら CPU 推奨（遅い）。

4.1 再現手順（例）

1. MNIST: `python src/run_benchmark.py --config config.yml --csv results/mnist.csv --json results/mnist.json`
2. KMNIST: `python src/run_benchmark_fashion.py --config config.yml --config-key kmnist_benchm --csv results/kmnist.csv --json results/kmnist.json`
3. EMNIST Letters: `python src/run_benchmark_fashion.py --config config.yml --config-key emnist_letters_benchmark --csv results/emnist.csv --json results/emnist.json`
4. CIFAR-10 (flat): `python src/run_benchmark_fashion.py --config config.yml --config-key cifar10_flat_benchmark --csv results/cifar10.csv --json results/cifar10.json`
5. Fashion-MNIST: `python src/run_benchmark_fashion.py --config config.yml --config-key fashion_complex --csv results/fmnist.csv --json results/fmnist.json`
6. 解析・図: `python scripts/analyze_benchmark.py`

5 結果概要

5.1 集計（5 データセット平均、各データセットはノイズグリッド平均）

データセット k の平均精度は

$$a_k = \frac{1}{|\Sigma_k|} \sum_{\sigma \in \Sigma_k} \mathrm{Acc}(k, \sigma),$$

集計の acc_mean は 5 データセット平均。デジタル基準は $\Sigma_k = \{0\}$ で通常推論のみ。

Model	acc_mean	acc_min	acc_max	diff (spread)
digital	0.8359	0.8359	0.8359	N/A (no noise)
amplitude	0.8302	0.8158	0.8343	0.0185
amplitude_noiseaware	0.8329	0.8310	0.8341	0.0031
phase	0.6156	0.2125	0.8406	0.6281
phase_noiseaware	0.8002	0.6964	0.8207	0.1243

Table 1: 5 データセット集計。spread は単一サンプル曲線の max–min。デジタルには推論ノイズを入れていない。

Dataset	digital	amplitude	amp_noiseaware	phase	phase_noiseaware
MNIST	0.9760	0.9730	0.9721	0.7842	0.9488
KMNIST	0.8913	0.8797	0.8878	0.7454	0.8530
EMNIST	0.9033	0.9009	0.8985	0.5690	0.8923
CIFAR10	0.5189	0.5149	0.5218	0.3119	0.4515
FMNIST	0.8899	0.8825	0.8844	0.6675	0.8553

Table 2: データセット別平均精度（評価ノイズグリッド平均）。

Dataset	digital	amplitude	amp_noiseaware	phase	phase_noiseaware
MNIST	0.0000	0.0081	0.0016	0.7033	0.1717
KMNIST	0.0000	0.0087	0.0055	0.5855	0.1781
EMNIST	0.0000	0.0339	0.0043	0.7881	0.0475
CIFAR10	0.0000	0.0250	0.0018	0.4011	0.0590
FMNIST	0.0000	0.0168	0.0024	0.6624	0.1652

Table 3: データセット別 spread（ノイズグリッド上の max–min、各 $\sigma 1$ サンプル）。

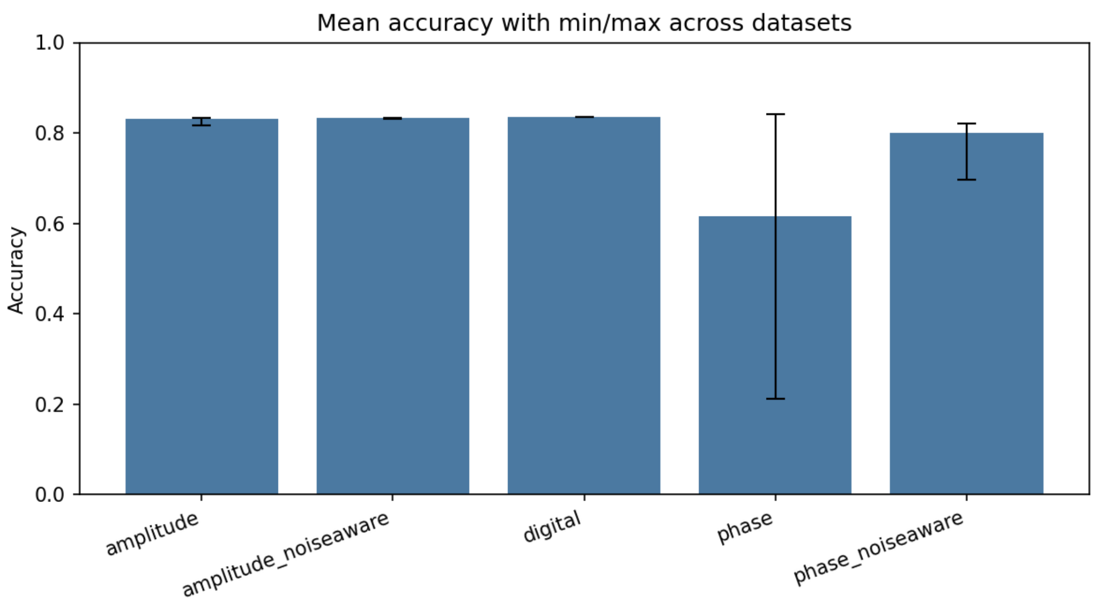

Figure 1: 平均精度（各モデルの min/max エラーバー付き）。

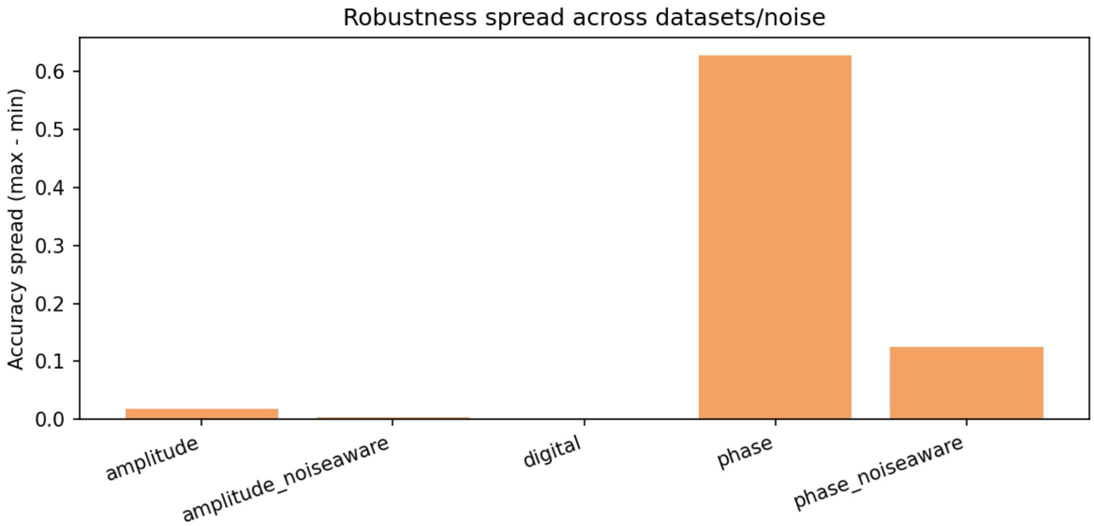

Figure 2: spread（max–min）。粗い頑健性診断。

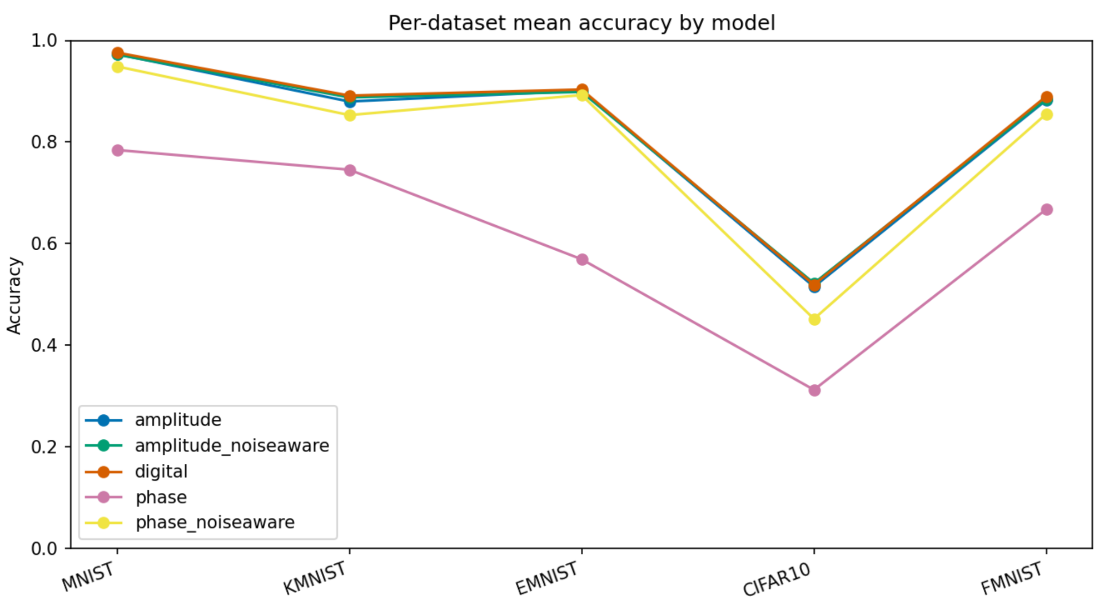

Figure 3: データセット別平均精度。

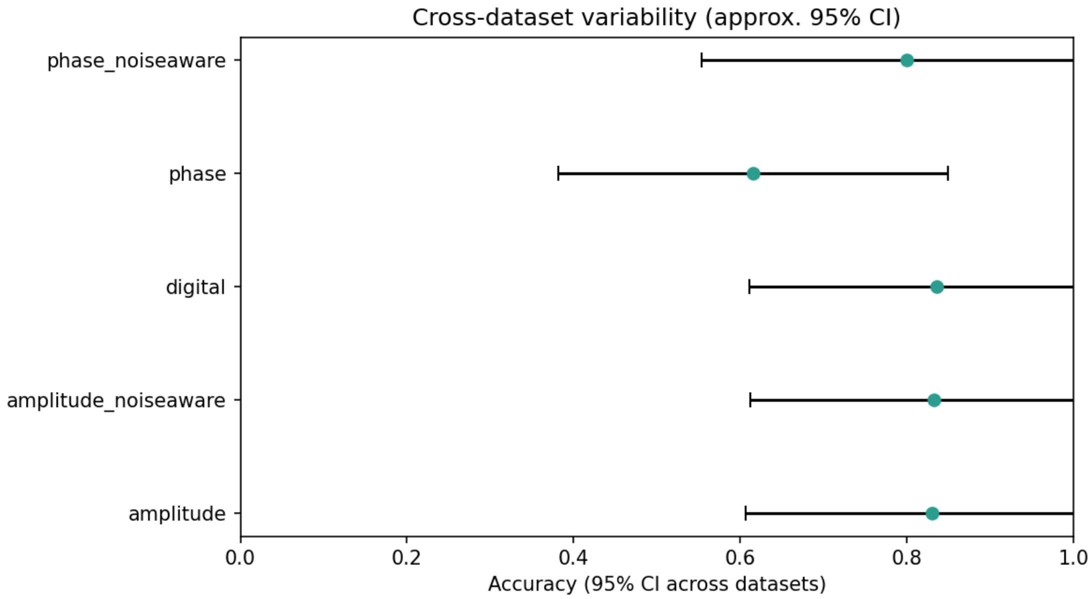

Figure 4: データセット間の変動区間（t ベース、記述的）。

5.2　データセット別平均と spread（単一シード、各 σ1 サンプル）

5.3　図

6　統計的視点

5 データセットの平均 $\bar{a}$ と標準偏差 s から t ベースの「変動区間」を示す：

$$\bar{a} \pm t_{0.975,4}\frac{s}{\sqrt{5}}.$$

これは**記述的な変動幅**であり、確率的な信頼区間ではない（精度は $[0,1]$ に制約される）。結果: digital 0.8359 ± 0.2244、amplitude 0.8302 ± 0.2238、amplitude_noiseaware 0.8329 ± 0.2205、phase 0.6156 ± 0.2343、phase_noiseaware 0.8002 ± 0.2467。デジタルの spread はノイズを入れていないため未定義。

7　考察

- **乗算ノイズ系**: amplitude_noiseaware はデジタルと僅差で、spread も最小。乗算ノイズを学習時に注入することが推論安定化に効く。
- **位相系**: ノイズなし学習は大きく不安定。ノイズあり学習で大幅改善するが、$\cos(\theta)$ という有界重み表現ゆえ容量不足気味で、CIFAR-10(flat) で顕著に遅れ。
- **指標の限界**: spread はノイズグリッドと単一サンプルに依存する粗い診断であり、厳密な頑健性指標ではない。

8　今後の改善と制約

- デジタルにも同じノイズを入れた対照実験（推論ノイズ・ノイズ付き学習）を追加し、エンコード効果と正則化効果を分離する。
- 複数シード・各 σ 複数サンプル、最悪値や AUC などの頑健性指標を報告する。
- 位相表現の容量拡張（$w = \alpha \cos\theta$、I/Q 表現）やラップド分布の検討。
- CIFAR-10(flat) は MLP 容量のストレステストに過ぎないため、畳み込み特徴と組み合わせた評価を行う。

9　結論

単一シード・各 σ1 サンプル・固定ノイズグリッドという前提のもと、乗算ノイズを伴う学習（amplitude_noiseaware）が最もバランスの取れた結果を示し、デジタル基準に近い精度と低い変動を両立した。位相モデルはノイズを伴う学習が必須で、$\cos(\theta)$ の有界表現では難しいタスクで劣る。今後は対照実験（デジタル + ノイズ）、複数シード、表現力強化（畳み込み特徴・位相の I/Q 表現）を行う。

謝辞

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参考文献（ドラフト）

Title	Year	Src.	Note
A Tutorial about Random Neural Networks in Supervised Learning (`http://arxiv.org/abs/1609.04846v1`)	2016	arXiv	Random neural networks / queueing view.
Predicting concentration levels of air pollutants by transfer learning and recurrent neural network (`http://arxiv.org/abs/2502.01654v1`)	2025	arXiv	Air pollution prediction.
Analog Alchemy: Neural Computation with In-Memory Inference, Learning and Routing (`http://arxiv.org/abs/2412.20848v1`)	2024	arXiv	In-memory analog neural computation and routing.
Masked Conditional Neural Networks for Audio Classification (`http://arxiv.org/abs/1803.02421v2`)	2018	arXiv	Conditional/masked neural networks for temporal signals.
The Deep Arbitrary Polynomial Chaos Neural Network (`http://arxiv.org/abs/2306.14753v1`)	2023	arXiv	Homogeneous chaos theory applied to deep networks.
A Neural Network-Evolutionary Computational Framework for RUL Estimation (`http://arxiv.org/abs/1905.05918v1`)	2019	arXiv	Remaining useful life estimation.
Memristors – from In-memory computing to Neuromorphic Computing (`http://arxiv.org/abs/2004.14942v1`)	2020	arXiv	Survey of memristor-based computing.
Reservoir Memory Machines as Neural Computers (`http://arxiv.org/abs/2009.06342v2`)	2020	arXiv	Differentiable neural computers with explicit memory.

Title	Year	Src.	Note
Adversarial Frontier Stitching for Remote Neural Network Watermarking (http://arxiv.org/abs/1711.01894v2)	2017	arXiv	Watermarking neural networks via adversarial stitching.
A Review on Neural Network Models of Schizophrenia and ASD (http://arxiv.org/abs/1906.10015v2)	2019	arXiv	Survey of NN models of ASD and schizophrenia.
Structure Is Not Enough: Leveraging Behavior for Neural Network Weight Reconstruction (http://arxiv.org/abs/2503.17138v1)	2025	arXiv	Weight reconstruction using behavioral cues.
Adiabatic Fine-Tuning of Neural Quantum States (http://arxiv.org/abs/2503.17140v2)	2025	arXiv	Neural quantum states and phase transitions in weight space.
Encoding binary neural codes in networks of threshold-linear neurons (http://arxiv.org/abs/1212.0031v3)	2012	arXiv	Encoding patterns via synaptic connections.
Recursive Self-Similarity in Deep Weight Spaces of Neural Architectures (http://arxiv.org/abs/2503.14298v1)	2025	arXiv	Fractal/coarse geometry perspective on deep weight spaces.
Development of a sensory-neural network for medical diagnosing (http://arxiv.org/abs/1807.02477v1)	2018	arXiv	Sensory-neural network for diagnostics.
Normalisation of Weights and Firing Rates in Spiking Neural Networks with STDP (http://arxiv.org/abs/1910.00122v1)	2019	arXiv	Spiking homeostasis and normalization.
Implementing a Bayes Filter in a Neural Circuit (http://arxiv.org/abs/1512.07839v4)	2015	arXiv	Bayesian filtering with neural circuits.
On functions computed on trees (http://arxiv.org/abs/1904.02309v4)	2019	arXiv	Hierarchical function compositions on trees.
Coherent states for compact Lie groups and their large-N limits (http://arxiv.org/abs/1707.02355v1)	2017	arXiv	Survey of heat-kernel coherent states.
Cognitive computation with autonomously active neural networks (http://arxiv.org/abs/0901.3028v1)	2009	arXiv	Self-sustained neural activity and cognition.
Coherent states in fermionic Fock-Krein spaces and their amplitudes (http://arxiv.org/abs/1708.03047v2)	2017	arXiv	Fermionic coherent states with indefinite inner products.
Review of Entangled Coherent States (http://arxiv.org/abs/1112.1778v1)	2011	arXiv	Survey of entangled coherent states.
Accumulate: An identity-based blockchain protocol (http://arxiv.org/abs/2204.06878v2)	2022	arXiv	DPoS blockchain with identity and cross-chain support.
Linear Delay-cell Design for Low-energy Delay Multiplication and Accumulation (http://arxiv.org/abs/2007.13895v3)	2020	arXiv	Low-energy MAC design.
MultiPLY: A Multisensory Object-Centric Embodied LLM in 3D World (http://arxiv.org/abs/2401.08577v1)	2024	arXiv	Multisensory object-centric embodied model.
AutoLungDx: A Hybrid Deep Learning Approach for Early Lung Cancer Diagnosis (http://arxiv.org/abs/2305.00046v4)	2023	arXiv	Hybrid 3D Res-U-Net/YOLOv5/ViT for lung cancer.
On the Capacity Region of the Two-User Interference Channel (http://arxiv.org/abs/1302.1837v1)	2013	arXiv	Interference channel capacity region.
A Multi-Stage Hybrid CNN-Transformer Network for Pediatric Lung Sound Classification (http://arxiv.org/abs/2507.20408v2)	2025	arXiv	Hybrid CNN-Transformer for lung sounds.
Interference Mitigation through Limited Transmitter Cooperation (http://arxiv.org/abs/1004.5421v1)	2010	arXiv	Cooperation strategies for interference mitigation.

Title	Year	Src.	Note
A Self-Attention-Driven Deep Denoiser Model for Real Time Lung Sound Denoising (http://arxiv.org/abs/2404.04365v3)	2024	arXiv	Self-attention denoiser for lung sounds.
Call to Protect the Dark and Quiet Sky from Satellite Constellations (http://arxiv.org/abs/2412.08244v2)	2024	arXiv	Impact of satellite constellations on sky observations.
ResCap-DBP: Lightweight Residual-Capsule Network for DNA-Binding Protein Prediction (http://arxiv.org/abs/2507.20426v1)	2025	arXiv	Residual-capsule network for DBP prediction.
Piecewise Semi-Analytical Formulation for Coupled-Oscillator Systems (http://arxiv.org/abs/2404.12780v1)	2024	arXiv	Semi-analytical solutions for coupled oscillators.
How transferable are features in deep neural networks? (http://arxiv.org/abs/1411.1792v1)	2014	arXiv	Feature transferability in deep nets.
Parallel Neural Networks in Golang (http://arxiv.org/abs/2304.09590v1)	2023	arXiv	PNNs implemented in Go.
Dual Accuracy-Quality-Driven Neural Network for Prediction Interval Generation (http://arxiv.org/abs/2212.06370v4)	2022	arXiv	Uncertainty quantification with dual objectives.
Synchronization conditions in the Kuramoto model (http://arxiv.org/abs/2007.04343v2)	2020	arXiv	Synchronization conditions and seminorms.
Conformal Group Actions on Generalized Kuramoto Oscillators (http://arxiv.org/abs/1812.06539v3)	2018	arXiv	Group actions on generalized Kuramoto models.
Synchronization of Kuramoto Oscillators on Knots (http://arxiv.org/abs/1104.3493v2)	2011	arXiv	Knot-based oscillator synchronization.
Compute and Energy Consumption Trends in Deep Learning Inference (http://arxiv.org/abs/2109.05472v2)	2021	arXiv	Trends in compute and energy for DL inference.
Cold Start Latency in Serverless Computing (http://arxiv.org/abs/2310.08437v2)	2023	arXiv	Review of cold start latency in serverless.
Solving the Hamiltonian path problem with a light-based computer (http://arxiv.org/abs/0708.1512v1)	2007	arXiv	Optical approach to Hamiltonian path.
Quantum Computing: Vision and Challenges (http://arxiv.org/abs/2403.02240v5)	2024	arXiv	Vision and challenges in quantum computing.
Tierkreis: A Dataflow Framework for Hybrid Quantum-Classical Computing (http://arxiv.org/abs/2211.02350v1)	2022	arXiv	Dataflow framework for hybrid quantum-classical.
Synthetic Biology meets Neuromorphic Computing (http://arxiv.org/abs/2504.10053v2)	2025	arXiv	Bio-inspired olfactory perception system.
Double Robust Semi-Supervised Inference for the Mean (http://arxiv.org/abs/2104.06667v2)	2021	arXiv	Semi-supervised inference under MAR labeling.
A Comparative Study of Load Balancing Algorithms in Cloud Computing Environment (http://arxiv.org/abs/1403.6918v1)	2014	arXiv	Load balancing in cloud environments.
Universal Workers: A Vision for Eliminating Cold Starts in Serverless Computing (http://arxiv.org/abs/2505.19880v2)	2025	arXiv	Reducing cold starts in serverless computing.
Placement of Microservices-based IoT Applications in Fog Computing (http://arxiv.org/abs/2207.05399v2)	2022	arXiv	Taxonomy for fog computing placement.
Driven spin wave modes in XY ferromagnet (http://arxiv.org/abs/1706.01619v6)	2017	arXiv	Nonequilibrium phase transition in XY ferromagnets.

Title	Year	Src.	Note
Room temperature reversible colossal volto-magnetic effect (http://arxiv.org/abs/2308.04324v1)	2023	arXiv	Volto-magnetic effect in oxide heterostructures.
Reversible Computing with Fast, Fully Static, Fully Adiabatic CMOS (http://arxiv.org/abs/2009.00448v2)	2020	arXiv	Energy-efficient reversible CMOS.
Monte Carlo study of the phase transitions in the classical XY ferromagnets (http://arxiv.org/abs/2208.10109v8)	2022	arXiv	Monte Carlo of anisotropic XY ferromagnets.
Supporting Multi-Cloud in Serverless Computing (http://arxiv.org/abs/2209.09367v4)	2022	arXiv	Multi-cloud strategies for serverless.
Bridging Phases at the Morphotropic Boundaries of Lead-Oxide Solid Solutions (http://arxiv.org/abs/cond-mat/0511256v1)	2005	arXiv	Piezoelectric solid solutions near morphotropic boundaries.
Graph Neural Networks Based Analog Circuit Link Prediction (http://arxiv.org/abs/2504.10240v5)	2025	arXiv	GNNs for analog circuit link prediction.
Partially Oblivious Neural Network Inference (http://arxiv.org/abs/2210.15189v1)	2022	arXiv	Oblivious inference for privacy.
A Metalearned Neural Circuit for Nonparametric Bayesian Inference (http://arxiv.org/abs/2311.14601v1)	2023	arXiv	Meta-learned neural circuit for Bayesian inference.
On the Accuracy of Analog Neural Network Inference Accelerators (http://arxiv.org/abs/2109.01262v3)	2021	arXiv	Accuracy analysis of analog NN accelerators.
DiffCkt: A Diffusion Model-Based Hybrid Neural Network Framework for Automatic Transistor-Level Generation of Analog Circuits (http://arxiv.org/abs/2507.00444v2)	2025	arXiv	Diffusion + hybrid NN for analog circuit generation.
The CEPC input for the European Strategy for Particle Physics - Accelerator (http://arxiv.org/abs/1901.03169v1)	2019	arXiv	CEPC accelerator design summary.
Applications of Particle Accelerators (http://arxiv.org/abs/2407.10216v1)	2024	arXiv	Overview of particle accelerator applications.
Accelerator design concept for future neutrino facilities (http://arxiv.org/abs/0802.4023v2)	2008	arXiv	Scoping study findings for future neutrino facilities.
Time-domain and Frequency-domain Signals and their Analysis (http://arxiv.org/abs/2009.14544v2)	2020	arXiv	Signals in time/frequency domains.
Fixed-Field Alternating-Gradient Accelerators (http://arxiv.org/abs/1604.05221v1)	2016	arXiv	Overview of FFAG accelerators for medical applications.
Training of mixed-signal optical convolutional neural network with reduced quantization level (http://arxiv.org/abs/2008.09206v1)	2020	arXiv	Mixed-signal optical CNN training.
Analog, In-memory Compute Architectures for Artificial Intelligence (http://arxiv.org/abs/2302.06417v1)	2023	arXiv	Energy-efficiency limits in analog in-memory computing.
HZO-based FerroNEMS MAC for In-Memory Computing (http://arxiv.org/abs/2208.06499v1)	2022	arXiv	Ferroelectric NEMS unimorph for low-energy MAC.
MRAM-based Analog Sigmoid Function for In-memory Computing (http://arxiv.org/abs/2204.09918v1)	2022	arXiv	Analog sigmoid using MRAM.
An Asynchronous Multi-Beam MAC Protocol for Multi-Hop Wireless Networks (http://arxiv.org/abs/2111.10073v1)	2021	arXiv	Multi-beam MAC for wireless networks.

Title	Year	Src.	Note
Wireless sensors networks MAC protocols analysis (`http://arxiv.org/abs/1004.4600v1`)	2010	arXiv	MAC protocols for wireless sensor networks.
Energy Efficient Dual Designs of FeFET-Based Analog In-Memory Computing (`http://arxiv.org/abs/2410.19593v1`)	2024	arXiv	FeFET-based IMC with shift-add capability.
LionHeart: A Layer-based Mapping Framework for Heterogeneous Systems with Analog In-Memory Computing Tiles (`http://arxiv.org/abs/2401.09420v3`)	2024	arXiv	Mapping framework for analog IMC tiles.
Nonlinear Integrated Microwave Photonics (`http://arxiv.org/abs/1310.4897v1`)	2013	arXiv	Nonlinear optical effects on chip.
Crosstalk Reduction for Superconducting Microwave Resonator Arrays (`http://arxiv.org/abs/1206.5571v1`)	2012	arXiv	Crosstalk reduction in MKIDs.
Near-Field Microwave Microscopy of Materials Properties (`http://arxiv.org/abs/cond-mat/0001075v2`)	2000	arXiv	Near-field microwave microscopy.
Bell-state measurement and quantum teleportation using linear optics (`http://arxiv.org/abs/1304.1214v1`)	2013	arXiv	Bell-state measurement and teleportation schemes.
Enabling Scalable Photonic Tensor Cores with Polarization-Domain Photonic Computing (`http://arxiv.org/abs/2501.18886v1`)	2025	arXiv	Polarization-domain photonic tensor core.
Highly-coherent stimulated phonon oscillations in a multi-core optical fiber (`http://arxiv.org/abs/1811.06290v1`)	2018	arXiv	Coherent acoustic waves in multi-core fiber.
The COHERENT Experiment at the Spallation Neutron Source (`http://arxiv.org/abs/1509.08702v2`)	2015	arXiv	COHERENT CEvNS experiment overview.
CORE – a COmpact detectoR for the EIC (`http://arxiv.org/abs/2209.00496v1`)	2022	arXiv	CORE detector proposal for EIC.
COHERENT Collaboration data release from the first detection of CEvNS on argon (`http://arxiv.org/abs/2006.12659v2`)	2020	arXiv	COHERENT argon CEvNS data release.
An optical fiber-based probe for photonic crystal microcavities (`http://arxiv.org/abs/physics/0406129v1`)	2004	arXiv	Fiber probe for photonic crystal cavities.
Photovoltaic-ferroelectric materials for the realization of all-optical devices (`http://arxiv.org/abs/2203.06515v1`)	2022	arXiv	Photovoltaic-ferroelectric materials for optical devices.
Frequency Ratio Measurements with 18-digit Accuracy Using a Network of Optical Clocks (`http://arxiv.org/abs/2005.14694v1`)	2020	arXiv	Optical clock frequency ratio measurements.
A Fast, robust algorithm for power line interference cancellation in neural recording (`http://arxiv.org/abs/1402.6862v2`)	2014	arXiv	Power line interference cancellation.
Understanding and mitigating noise in trained deep neural networks (`http://arxiv.org/abs/2103.07413v3`)	2021	arXiv	Noise in trained DNNs and mitigation.
Denoising Noisy Neural Networks: A Bayesian Approach with Compensation (`http://arxiv.org/abs/2105.10699v3`)	2021	arXiv	Bayesian denoising for noisy neural networks.
Noise and Bell's inequality (`http://arxiv.org/abs/1008.0667v2`)	2010	arXiv	Noise considerations in Bell tests.
Quantum and Classical Frontiers of Noise (`http://arxiv.org/abs/1612.03430v1`)	2016	arXiv	Survey of quantum/classical noise frontiers.

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Noise based logic: why noise? (http://arxiv.org/abs/1204.2545v4)	2012	arXiv	Noise-based logic and randomness.
Decoherence and noise in open quantum system dynamics (http://arxiv.org/abs/1605.07838v1)	2016	arXiv	Decoherence and noise in open systems.
Instantaneous noise-based logic (http://arxiv.org/abs/1004.2652v2)	2010	arXiv	Deterministic logic with binary noise timefunctions.
Noise Dynamics in the Quantum Regime (http://arxiv.org/abs/2311.17794v1)	2023	arXiv	Time-dependent modulation of current fluctuations.
Simple Cracking of (Noise-Based) Dynamic Watermarking in Smart Grids (http://arxiv.org/abs/2406.15494v3)	2024	arXiv	Security analysis of noise-based watermarking.
Phase-Locked, Low-Noise, Frequency Agile Titanium: Sapphire Lasers (http://arxiv.org/abs/physics/0507187v2)	2005	arXiv	Phase-locked Ti:sapphire lasers with low noise.
Stokes' Drift and Hypersensitive Response with Dichotomous Markov Noise (http://arxiv.org/abs/cond-mat/0501499v1)	2005	arXiv	Stochastic Stokes' drift under dichotomous noise.
Shot noise for entangled and spin-polarized electrons (http://arxiv.org/abs/cond-mat/0210498v1)	2002	arXiv	Shot noise in entangled/spin-polarized transport.
The Data Conversion Bottleneck in Analog Computing Accelerators (http://arxiv.org/abs/2308.01719v4)	2023	arXiv	Data conversion limits in analog accelerators.
Analysis of Performance of Linear Analog Codes (http://arxiv.org/abs/1511.05509v2)	2015	arXiv	MSE performance bounds for linear analog codes.
Security of quantum key distribution with detection-efficiency mismatch (http://arxiv.org/abs/1810.04663v3)	2018	arXiv	Bounds for QKD with detector mismatch.
Performance Analysis of the Matrix Pair Beamformer with Matrix Mismatch (http://arxiv.org/abs/1009.5979v4)	2010	arXiv	Robustness of matrix pair beamformer.
The three and a half layers of dynamics : analog, digital, semi-digital, analog (http://arxiv.org/abs/1106.0911v1)	2011	arXiv	Perspective on analog/digital dynamics.
Are Bohmian trajectories real? (http://arxiv.org/abs/quant-ph/0609172v2)	2006	arXiv	Bohmian trajectories and classical mismatch.
Computation over Mismatched Channels (http://arxiv.org/abs/1204.5059v2)	2012	arXiv	Distributed computation over MAC with mismatch.
Superfluid Analog of the Davies-Unruh Effect (http://arxiv.org/abs/gr-qc/0505005v1)	2005	arXiv	Analog of Davies-Unruh in superfluid helium.
Semantic Communications with Discrete-time Analog Transmission: A PAPR Perspective (http://arxiv.org/abs/2208.08342v3)	2022	arXiv	Semantic communications with analog transmission.
Programmable photonic circuits (https://doi.org/10.1038/s41566-020-0585-z)	2020	bib	Overview of programmable photonic circuits.
Coupled oscillators for computing: A review and perspective (https://doi.org/10.1063/1.5108897)	2020	bib	Review of coupled oscillator computing.
Parallel convolutional processing using an integrated photonic tensor core (https://doi.org/10.1038/s41586-020-03070-1)	2021	bib	Photonic tensor core for convolutions.

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Oscillatory neurocomputers with dynamic connectivity (https://doi.org/10.1126/science.283.5408.1903)	1999	bib	Oscillatory neurocomputer concept.
A 65nm 4.7TOPS/W 8bit CNN processor with mixed-signal computing (https://doi.org/10.1109/ISSCC.2018.8310344)	2018	bib	Mixed-signal CNN accelerator with calibration.
All-optical machine learning using diffractive deep neural networks (https://doi.org/10.1126/science.aat8084)	2018	bib	Diffractive optical layers performing inference.
Noise mitigation in analog in-memory computing for deep neural network accelerators (https://doi.org/10.1109/JXCDC.2021.3090030)	2021	bib	Noise mitigation for analog IMC accelerators.
Experimental demonstration of reservoir computing on a silicon photonics chip (https://doi.org/10.1038/ncomms3541)	2014	bib	Photonic reservoir computing demonstration.
Broadcast and weight: An integrated network for scalable photonic spike processing (https://doi.org/10.1038/srep05522)	2014	bib	Photonic weighting for neuromorphic spikes.
Optimal design for universal multiport interferometers (https://doi.org/10.1364/OPTICA.3.001460)	2016	bib	Mesh design for programmable interferometers.
Memory devices and applications for in-memory computing (https://doi.org/10.1038/s41565-020-0655-z)	2020	bib	Survey of memory devices for IMC.
Deep learning with coherent nanophotonic circuits (https://doi.org/10.1038/nphoton.2017.93)	2017	bib	Phase-programmable nanophotonic interferometer.
Neuromorphic photonic networks using silicon photonic weight banks (https://doi.org/10.1038/s41598-017-06630-y)	2017	bib	Photonic weight banks for coherent summation.
An oscillator-based Ising machine (https://doi.org/10.1038/s41928-019-0300-0)	2019	bib	Oscillator-based Ising machine.
Deep physical neural networks trained with backpropagation (https://doi.org/10.1038/s41586-021-04223-6)	2022	bib	Backpropagation through physical systems.