Evo-SAN: Evolutionary Optimization and Co-design of Energy-efficient Neuromorphic Hardware Trigger for UHE Neutrino Detection

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I. Background & Motivation

- **Motivation:** The potential for detecting Ultra-high Energy (UHE) neutrinos with IceCube-Gen2 radio antennas depends critically on the trigger performance, which is energy- and computationally constrained due to the limited power of the stations.
- **Research question:** How much can the energy efficiency of the trigger be improved using analog and neuromorphic hardware co-design optimization?
- **Outcome:** Proof of concept that evolutionary optimization can be applied to the design space of SNNs for developing a real-time, lightweight, energy-efficient, event-driven thermal noise rejection, enhancing detection rates and event sampling.

Contributions:

- **Novel Evolutionary Pipeline:** A dual-policy evolutionary-based RL pipeline that relies on NEAT to generate and optimize the SNN while the critic network determines the most optimal action.
- **Event-driven Sampling:** Adaptive Sigma-Delta encoder-decoder in the loop to improve robustness to a wide range of thermal noise fluctuations.
- **DRL Co-supervision:** The addition of PSNR as a privilege observation for the critic network while leveraging boot-strapping to offer reduction of training time.

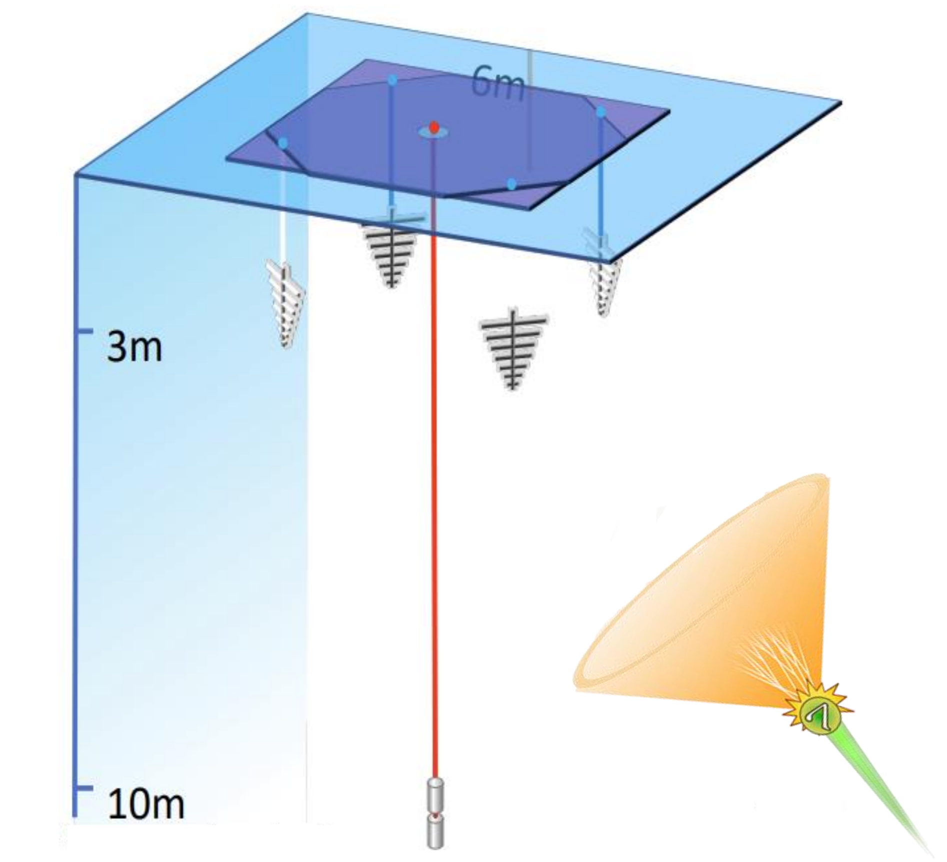

Fig. 1: Detector station in ARIANNA pilot with four Log-periodic Dipole Antennas (LPDAs). Final antenna stations need to be autonomous for remote long-term deployment in the Antarctic ice.

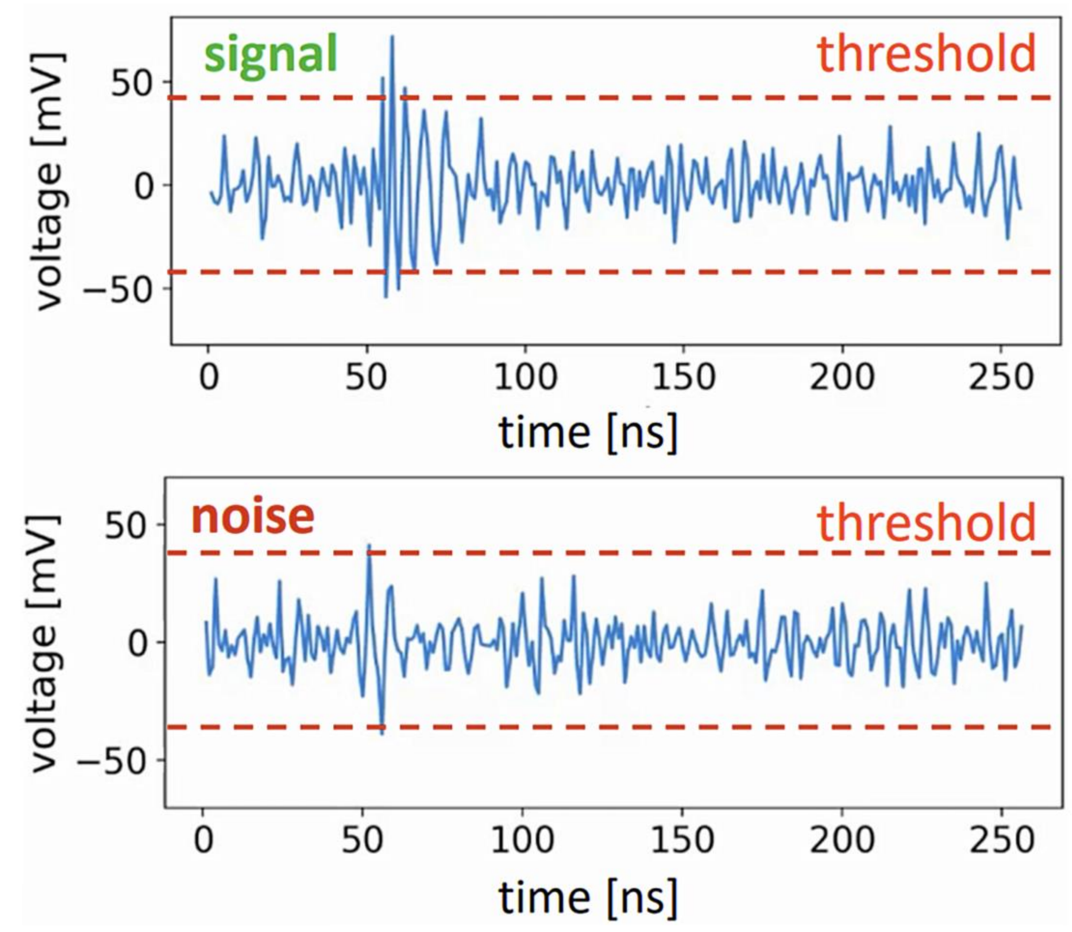

Fig. 2: Pulse shape discrimination for UHE neutrino detection.

II. Approach for Co-design Optimization

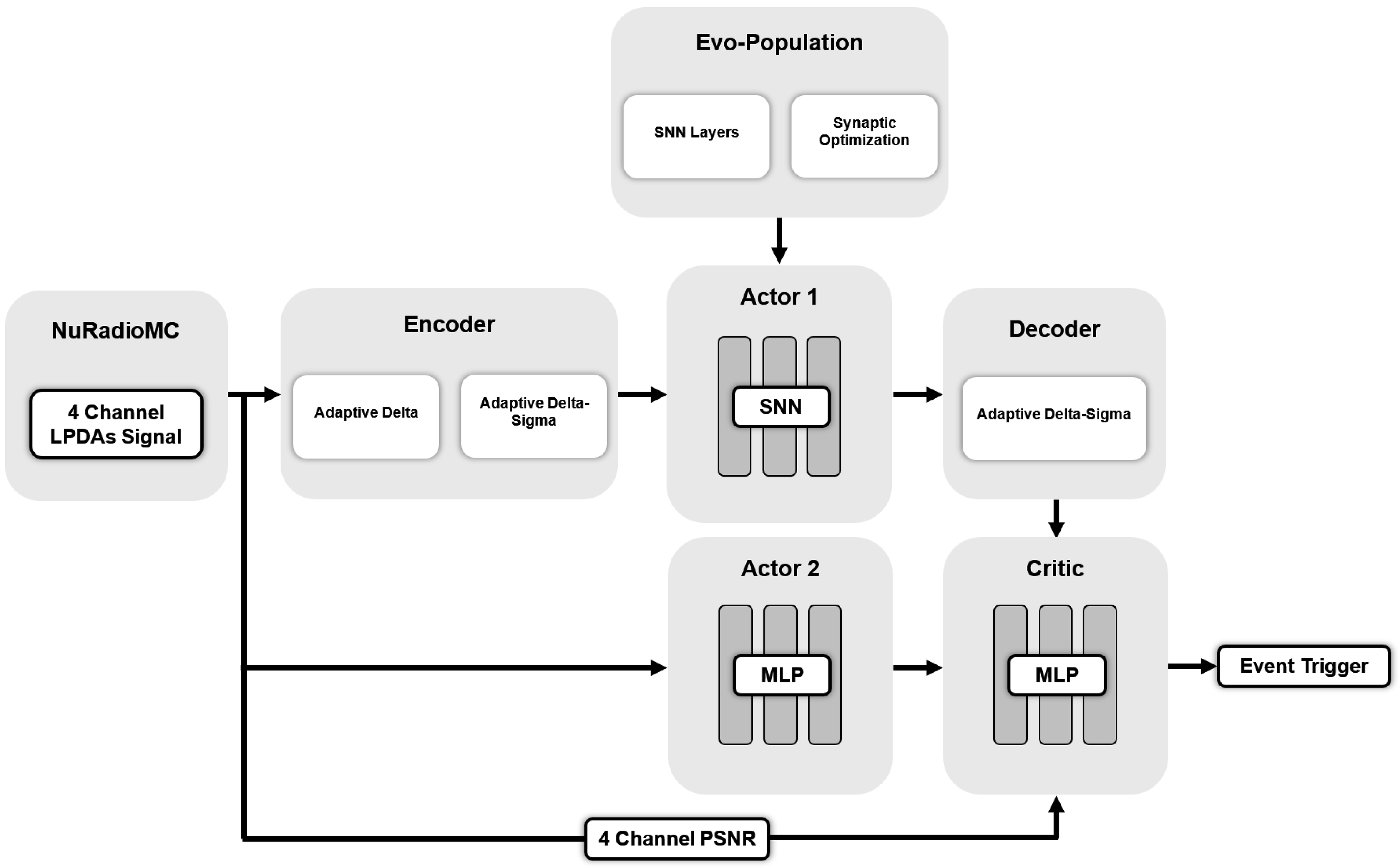

Fig. 3: The overall view of Evo-SAN pipeline which is composed of two actor networks, a single critic network for action selection based on privileged observation, and an evolutionary population generation based on Spike Neural Network (SNN).

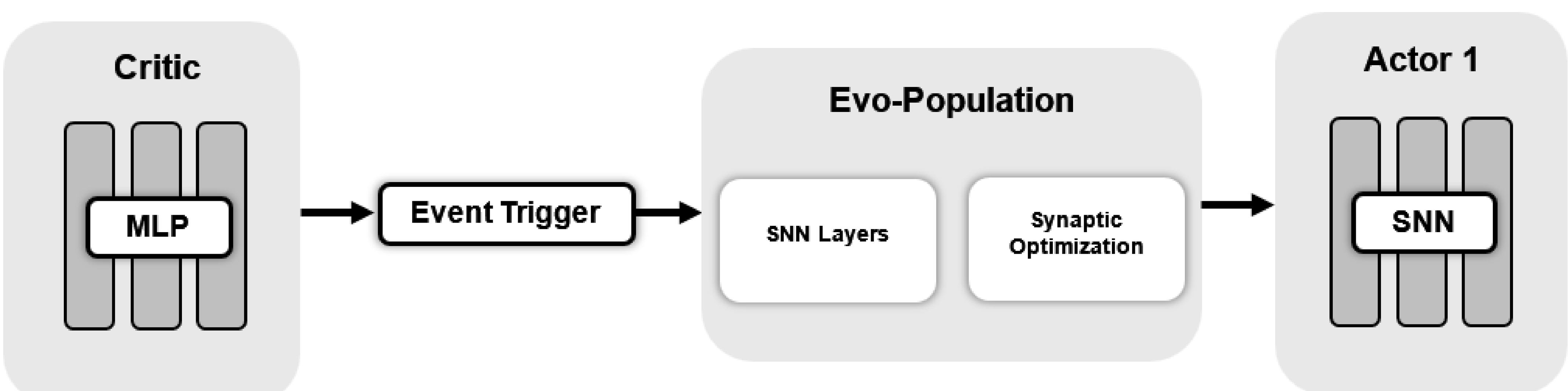

Fig. 4: The overview of evolutionary population generation based on event-driven sampling and its accuracy during the training phase.

III. Preliminary Results

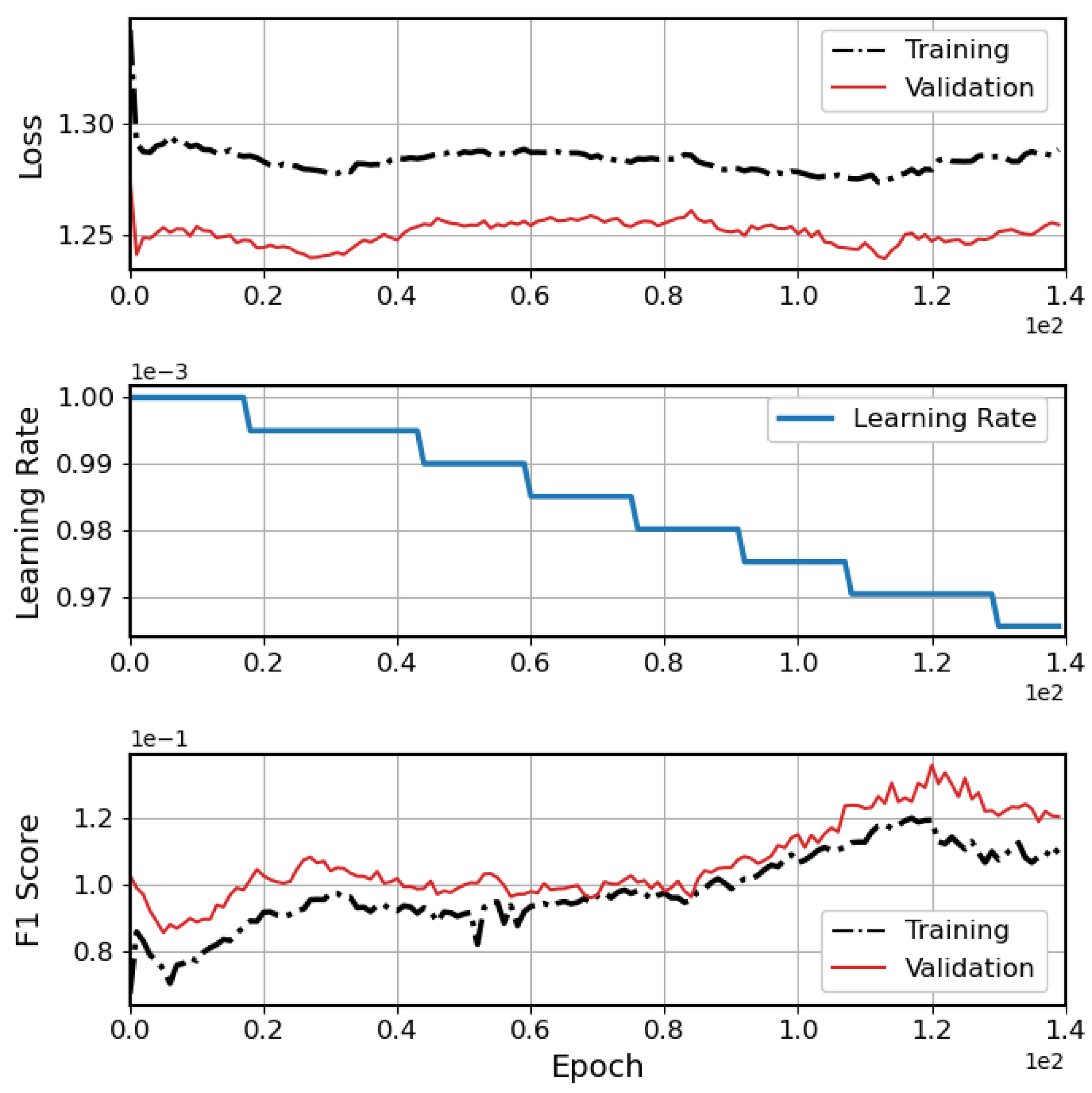

Fig. 5: Preliminary quantitative results of SNN for UHE neutrinos detection using simulated LPDAs in NuRadioMC with 10^{16} eV energy.

IV. Future Work

- **Encoder/Decoder:** Further investigation of various encoders and decoders and their combination to improve the detection rate while minimizing spike generation.
- **Neuron Models:** Analyze other SNN models such as Resonate and Fire (RF), Resonate and Fire Izhikevich (RFIz) and Adaptive Leaky Integrate and Fire (ALIF).
- **Fitness Function:** Modification of fitness function and reward design based on detection rate and related meta-cost to ensure energy-efficient sampling.

V. References

[1] A. Anker, et al., "Improving sensitivity of the ARIANNA detector by rejecting thermal noise with deep learning," in Journal of Instrumentation, vol. 17, no. 03, pp. P03007, 2022.

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[3] Glaser, C., et al. "NuRadioMC: simulating the radio emission of neutrinos from interaction to detector," in *The European Physical Journal C*, vol. 80, no. 2, 2020.

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