Autonomous Pulse Control for Quantum Transducers with Deep Reinforcement Learning

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Abstract: Quantum transducers are the back-bone technology and enabler for the Quantum Internet. We created a Deep Reinforcment Learning control framework to overcome current, low conversion efficiencies, bringing quantum transducers towards practical use.

1. Overview

Quantum networks are going to disrupt how we perceive super-computing networks. Quantum network test-bed programs prompt the development of advanced management and control strategies to distribute entanglement across a multi-node quantum network. Long-distance distribution of quantum information across a network needs preliminary demonstrations and exploration of quantum network applications, but is a challenge due to errors arising from decoherence channels in quantum network components. In this demo, we address these challenges through the development of advanced control routines that improve the Quality of Entanglement (QoE) between network nodes demonstrating a truly distributed quantum network.

Quantum operations on noisy quantum hardware are enhanced by firmware level optimization of microwave and optical control signals. These engineered pulses enhance the fidelity of quantum operations, leading to increased performance capability needed to demonstrate a quantum advantage on current quantum processors. In quantum physics, model-based optimization techniques, however, are insufficient due to the difficulty of modeling quantum systems coupled to decoherence channels. In this demo, we present AI solutions, particularly a Deep Reinforcement Learning (DRL) algorithm, to learn the best pulses to maximize quantum network performance.

Connecting quantum processors across a network requires the conversion of quantum information from microwave photons to optical photons [2]. Challenges for transduction of quantum information arise from the strong coupling needed between the microwave and optical bands. Laser induced heating of intermediary phononic modes that facilitate this coupling significantly reduces the conversion efficiency. To date, optomechanical quantum transduction yields the highest conversion efficiency of 47% [1].

Optomechanical transducers are composed of microwave and optical cavities coupled to a mechanical oscillator by a radiation pressure force. In a quantized setting the electromagnetic contributions are described using a Hamiltonian,

$$H = \omega_m b b^\dagger + \sum_{j=1}^{2} \left[\Delta_j a_j a_j^\dagger + g_j (b + b^\dagger) a_j^\dagger a_j + \Omega_j, (a_j + a_j^\dagger) \right] \tag{1}$$

with quantized creation (annihilation) operators for phonon modes $b^\dagger(b)$ and photon modes $a^\dagger(a)$ coupled non-linearly with an interaction strength g. The cavities are driven independently using an external electromagnetic field to pump the photons with amplitude Ω, and the cavities are red-detuned ($\Delta_j < 0$) by the laser frequency to enable cooling and photon-phonon exchange. The external field amplitudes can be modified in time using an arbitrary waveform generator (AWG) to counteract noise and dissipation effects which has not been implemented in current experimental platforms for optomechanical transducers.

2. Innovation

We created an original control model for optomechanical transducers using input-output theory,

$$\dot{\mathbf{a}} = A(t)\mathbf{a} + B\mathbf{a}_{in} \tag{2}$$

$$\mathbf{a}_{out} = C\mathbf{a} + D\mathbf{a}_{in}, \tag{3}$$

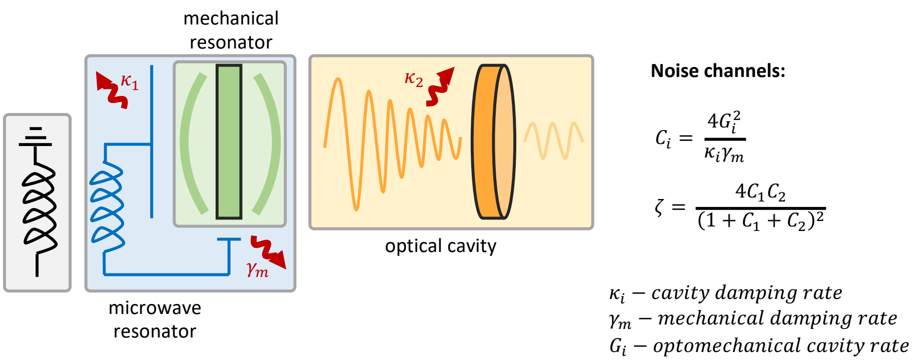

Fig. 1. Optomechanical quantum transducer. The theoretical efficiency metric ζ is composed of the cooperativity C of the two cavities.

to obtain the efficiency metric, $\zeta = \mathbf{a}_{out}/\mathbf{a}_{in}$, with a time-dependent drive. We reproduce the results of Ref [1] in simulation using the experimentally defined matrices A, B, C, D. Our model and simulation serves as a back end data generator and theoretical benchmark for our DRL control framework.

We are the first research team to implement and demonstrate DRL control for quantum networks. Our DRL framework is described by the actions an agent can take, the state of the system after the action, and the reward the agent receives after taking an action based on the state.

- *Actions* - real and imaginary amplitudes of the microwave and optical driving fields.
- *State/Observations* - photon operator amplitudes and average cavity photon number.
- *Reward* - efficiency of microwave to optical signal throughput.

Using a DDPG Actor-Critic Reinforcement Learning algorithm with a continuous state space and a multi-discrete action space we successfully trained an agent and demonstrated control with a trained neural network. Our research demonstrate the agent can determine pulse sequencing that can push the conversion efficiency towards unity.

3. OFC Relevance

Research contributions in machine learning and AI for network control is a fast growing domain at OFC. OFC is also seeing a growth in contributions in quantum networking with a quantum focused Rump Session expected for OFC 2022. Our research couples these two domains and opens new avenues to innovate quantum networking control protocols using AI tools.

4. Content and Implementation

We will conduct a live demonstration of our AI agent in action, delivering control solutions to optimize transduction efficiency for microwave and optical cavities in the presence of damping and noise. We will contribute a library of trained neural networks with different control schemes that attendees can run and test the robustness of the control solution. The demo will consist of one large monitor to display the agent in training and the algorithm, with an additional small monitor for the audience to interact with trained neural networks.

References

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2. Nikolai Lauk, Neil Sinclair, Shabir Barzanjeh, Jacob P. Covey, Mark Saffman, Maria Spiropulu, Christoph Simon, "Perspectives on quantum transduction," Quantum Sci. Technol., **5**, 020501 (2020).