

Quantum-based optimization of Reconfigurable Intelligent Surfaces: Barren Plateaus Analysis

E. Colella⁽¹⁾, L. Bastianelli⁽¹⁾, V. Mariani Primiani⁽¹⁾, F. Moglie⁽¹⁾, Z. Peng⁽²⁾, and G. Gradoni⁽³⁾

⁽¹⁾ Università Politecnica delle Marche, Marche, Italy

⁽²⁾ University of Illinois, USA

⁽³⁾ University of Surrey, Guildford, UK

Reconfigurable intelligent surface (RIS) optimization is a high-dimensional combinatorial problem, where classical methods face significant scalability challenges. The quantum approximate optimization algorithm (QAOA) offers a promising alternative by encoding the optimization problem into a quantum Hamiltonian and finding its ground state through a parameterized quantum circuit, known as the ansatz [1]. In the quantum framework, the RIS optimization problem is mapped onto the Sherrington-Kirkpatrick (SK) Hamiltonian, which models the transfer function between the transmitting antenna (TX) and the receiver (RX) [2, 3] as follows:

$$\hat{H}_{\text{RIS}} = - \sum_{i < j} J_{ij} \hat{Z}_i \hat{Z}_j, \quad (1)$$

where $\hat{Z}_i \in \{-1, +1\}$ corresponding to $\{-\pi, +\pi\}$ RIS cell phase shift and J_{ij} are the interaction coefficients. The RIS model is represented by the QAOA ansatz, a parameterized quantum circuit designed to prepare the quantum state $|\psi(\boldsymbol{\vartheta})\rangle$, where $\boldsymbol{\vartheta}$ denotes the variational parameters. Given the SK Hamiltonian and the QAOA ansatz (RIS model) for a 3×3 RIS ($N = 9$ qubits), the QAOA aims to minimize the cost function $C(\boldsymbol{\vartheta}) = \langle \psi(\boldsymbol{\vartheta}) | \hat{H}_{\text{RIS}} | \psi(\boldsymbol{\vartheta}) \rangle$, in order to determine the optimal parameters $\boldsymbol{\vartheta}$ that maximize the received signal intensity at a specific receiver position. After the training process, the QAOA-trained RIS model was tested on 30 different receiver positions, achieving optimal solutions in 29 cases. Gradient analysis for RIS sizes $N = 3 - 14$ revealed that the variance of the cost function gradient decreases exponentially with the number of RIS elements, confirming the theoretical prediction of barren plateaus (BP) [4]. The BP limitation arises from the flat optimization landscape, which hinders scalability in larger systems. Despite these challenges, QAOA demonstrates strong potential for RIS optimization in small to medium-sized systems, efficiently identifying near-optimal configurations. Future research will address scalability by exploring advanced ansatz designs and hybrid quantum-classical approaches to overcome the BP limitations enhancing smart radio performances.

References

- [1] E. Farhi, J. Goldstone, S. Gutmann, and L. Zhou, “The quantum approximate optimization algorithm and the Sherrington-Kirkpatrick model at infinite size,” *Quantum*, vol. 6, p. 759, 2022.
- [2] C. Ross, G. Gradoni, Q. J. Lim, and Z. Peng, “Engineering reflective metasurfaces with ising hamiltonian and quantum annealing,” *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 4, pp. 2841–2854, 2022.
- [3] E. Colella, L. Bastianelli, V. M. Primiani, Z. Peng, F. Moglie, and G. Gradoni, “Quantum optimization of reconfigurable intelligent surfaces for mitigating multipath fading in wireless networks,” *IEEE Journal on Multiscale and Multiphysics Computational Techniques*, vol. 9, pp. 403–414, 2024.
- [4] J. McClean, S. Boixo, V. Smelyanskiy, R. Babbush, and H. Neven, “Barren plateaus in quantum neural network training landscapes,” *Nature Communications*, vol. 9, 11 2018.