Quantum-Assisted Beamforming Optimization for Beyond-5G Networks

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ABSTRACT

Energy-efficient beamforming is essential for beyond-5G and emerging 6G wireless networks under strict quality-of-service constraints. This paper presents a quantum-assisted beamforming approach based on the Quantum Approximate Optimization Algorithm (QAOA) for transmit power minimization in MISO systems. The impact of QAOA circuit depth on convergence and power reduction is analyzed. Simulation results show that increased circuit depth improves convergence and energy efficiency under near-term quantum hardware constraints.

I. INTRODUCTION

Energy-efficient beamforming is a fundamental design objective for beyond-5G and emerging 6G wireless networks, particularly in multiple-input single-output (MISO) systems where dense antenna deployments and strict quality-of-service (QoS) requirements coexist. Beamforming enables spatial selectivity and interference mitigation but optimizing beamforming vectors under transmit power and SINR constraints remains a challenging task. Classical optimization techniques, such as convex optimization and iterative solvers, have been widely studied for this purpose; however, their practical applicability becomes limited as the problem dimensionality and combinatorial nature increase, especially under real-time constraints [1], [2].

Recently, quantum computing has emerged as a promising alternative computational paradigm for solving complex combinatorial optimization problems. In particular, the Quantum Approximate Optimization Algorithm (QAOA) has attracted attention due to its hybrid quantum-classical structure and suitability for quadratic unconstrained binary optimization (QUBO) formulations [3], [4]. Several proof-of-concept studies have demonstrated the potential of quantum-assisted optimization in wireless communication problems, including beamforming and resource allocation, using quantum simulators or near-term quantum devices [5]. In our previous work, QAOA was applied to transmit power minimization in MISO networks by formulating the beamforming selection problem as a QUBO, demonstrating promising power reduction compared to classical solvers under fixed algorithmic settings

Motivated by these observations, this paper presents an extension that focuses on understanding the impact of QAOA circuit depth on beamforming optimization performance. We aim to provide practical insights into how increasing circuit depth influences convergence behavior and transmit power reduction under near-term quantum constraints. Furthermore, we interpret the resulting power savings from an energy-efficiency perspective, aligning the study with green communication objectives for future wireless systems. Through simulation-based evaluation using a quantum simulator, this work offers early design guidelines for quantum-assisted beamforming optimization in MISO networks.

II. SYSTEM MODEL

We consider a downlink multiple-input single-output (MISO) communication system in which a base station (BS) equipped with N transmit antennas serves K single-antenna users. Linear beamforming is employed at the BS to deliver independent data streams to the users while satisfying their quality-of-service (QoS) requirements. Let $\mathbf{h}_k \in \mathbb{C}^{N\times 1}$ denote the channel vector between the BS and the k-th user. The transmitted signal is given by $\mathbf{x} = \sum_{k=1}^{K} \mathbf{w}_k s_k$, where $\mathbf{w}_k \in \mathbb{C}^{N\times 1}$ is the beamforming vector associated with user k, and s_k is the corresponding data symbol with unit average power. The received signal at the k-th user is expressed as

$$y_k = \mathbf{h}_k^H \mathbf{w}_k s_k + \sum_{j\neq k} \mathbf{h}_k^H \mathbf{w}_j s_j + n_k,$$

where n_k represents additive white Gaussian noise with variance σ_k^2. The signal-to-interference-plus-noise ratio (SINR) at user k is defined as

$$\mathrm{SINR}_k = \frac{|\mathbf{h}_k^H \mathbf{w}_k|^2}{\sum_{j\neq k} |\mathbf{h}_k^H \mathbf{w}_j|^2 + \sigma_k^2}.$$

The objective is to minimize the total transmit power at the BS while ensuring a minimum SINR requirement γ_k for each user. The total transmitted power is given by

$$P_{\text{total}} = \sum_{k=1}^{K} \| \mathbf{w}_k \|^2.$$

This power minimization problem subject to SINR constraints is non-convex and combinatorial in nature, motivating alternative optimization approaches beyond conventional solvers.

III. PROPOSED QUANTUM-ASSISTED OPTIMIZATION METHOD

To enable quantum-assisted optimization, the continuous beamforming vectors are discretized using a finite set of predefined basis vectors. Each beamforming vector is expressed as a binary-weighted combination of basis vectors as

$$\mathrm{w}_k = \sum_{l=1}^{L} b_{k,l}\, \mathrm{v}_{k,l}, b_{k,l} \in \{0,1\},$$

where $b_{k,l}$ denotes a binary decision variable indicating the selection of the l-th basis vector for user k. This discretization transforms the original beamforming problem into a QUBO problem.

The transmit power objective and SINR constraints are combined into a single cost function using penalty terms, resulting in a QUBO formulation that can be efficiently handled by quantum optimization algorithms. The QUBO problem is solved using the QAOA, a hybrid quantum-classical algorithm designed for combinatorial optimization. QAOA alternates between a problem-dependent cost Hamiltonian and a mixing Hamiltonian, with the goal of steering the quantum state toward low-energy solutions corresponding to optimized beamforming selections.

In this work, we focus on analyzing the impact of QAOA circuit depth, denoted by p, on optimization performance. The circuit depth determines the number of alternating applications of the cost and mixing operators and directly influences the expressiveness of the quantum circuit. Furthermore, the achieved power savings are interpreted from an energy-efficiency perspective, highlighting the relevance of quantum-assisted beamforming for energy-aware wireless system design.

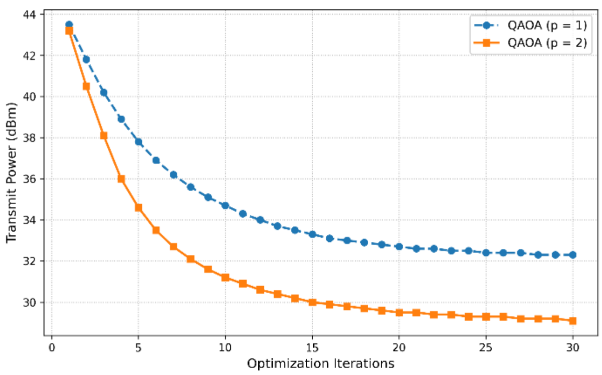

Figure 1: Convergence of QAOA-Based Beamforming for Different Circuit Depths

IV. SIMULATION RESULTS

The convergence behavior of the proposed QAOA-based beamforming optimization is illustrated in Fig. 1 for two circuit depths, $p = 1$ and $p = 2$. Both configurations achieve a gradual reduction in transmitting power over the optimization iterations, confirming the feasibility of QAOA for transmitting power minimization. However, the deeper circuit ($p = 2$) converges more rapidly and reaches a lower final transmit power compared to the shallow configuration ($p = 1$). This improvement is attributed to the increased expressiveness of higher-depth QAOA circuits, which enables more effective exploration of the solution space. Although deeper circuits incur higher quantum complexity, the observed power reduction directly implies improved energy efficiency at the base station.

V. CONCLUSION

This paper presented a study on quantum-assisted beamforming for transmit power minimization in MISO systems using QAOA. The impact of QAOA circuit depth on convergence and power reduction was analyzed, showing that deeper circuits achieve improved optimization performance. The resulting power savings also indicate potential energy-efficiency benefits for future wireless networks. These results provide early insights into quantum-assisted optimization under near-term quantum hardware constraints.

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