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Quantum Calculator on Circuit Optimization of Quantum Computing Using Qiskit

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Abstract

This paper introduces a comprehensive quantum calculator using Qiskit that integrates quantum arithmetic and logic functions into a single calculator. The calculator relies on quantum Fourier transforms (QFT), controlled-phase gates, and quantum modular arithmetic to perform basic arithmetic operations such as addition, subtraction, and multiplication. These arithmetic techniques used quantum parallelism and interference to perform calculations more efficiently, particularly for tasks involving large numerical inputs. Numerical values are stored in qubit registers and processed using QFT-based circuits, which enable efficient and reversible mathematical computations. In addition to arithmetic operations, the calculator also implements quantum logic algorithms, including Grover's Search and the Deutsch-Jozsa algorithm. Grover's algorithm is an unstructured search algorithm that operates by constructing an oracle and iteratively amplifying the probability amplitude of the target solution. This amplitude amplification significantly increases the likelihood of measuring the desired outcome. Due to this property, Grover's algorithm has practical relevance in applications such as database searching and solving combinatorial optimization problems. The Deutsch-Jozsa algorithm determines whether or not a certain Boolean function is constant or balanced and offers an exponential speed up compared to classical methods for this class of problem. A key fundamental function of the calculator is the ability to generate hybrid quantum circuits that support both arithmetic and logical functions. That allows the exploration of simple as well as complex problem-solving strategies that take advantage of both quantum arithmetic and decision-making algorithms. For instance, combining Grover's amplification with function characterizations from the Deutsch-Jozsa algorithm provides not only interesting circuit configurations but also adds value to the possibilities of the algorithms. This research offers a modular idea and allows exploring the fundamental principles of quantum computing generally speaking and will be a valuable resource for educational as well as research purposes in the rapidly growing field of quantum algorithm development.

Categories: Quantum Algorithms, Quantum Computing, Security and Privacy
Keywords: quantum computing, quantum methodology, quantum algorthim, qiskit, circuit optimization

Introduction

Quantum computing is the revolutionary fusion of quantum mechanics and computer science, providing new pathways to solve complex problems. Unlike classical bits, quantum bits (qubits) propagate information through probabilistic amplitudes by using superposition and entanglement. The advantages of these features allow quantum systems to carry out tasks that cannot be performed in a classical way. In the era of Noisy Intermediate-Scale Quantum (NISQ) devices, optimizing circuits is important to reduce error rates and quantum computational complexity. Otherwise, poorly designed circuits are prone to excessive noise and underperformance. There is an urgent need for sophisticated tools for circuit design, simulation, and execution. For this reason, we construct a quantum calculator using Qiskit, a popular open-source quantum computing framework created by IBM. In this work, the quantum calculator aims to perform arithmetic and logical quantum functions, providing a useful avenue for exploring quantum computing models.

In the case of arithmetic functions, the calculator performs operations such as addition, subtraction, and multiplication using quantum circuits. These functions employ quantum logic techniques, such as the Quantum Fourier Transform (QFT) and controlled gates, to perform calculations more efficiently. The calculator includes several foundational quantum algorithms from a pragmatic perspective, including Grover's Search and the Deutsch-Jozsa algorithm. Grover's algorithm is a quantum search algorithm that exhibits quadratic speedup over classical search methods for unstructured databases. The Deutsch-Jozsa algorithm demonstrates exponential speedup by determining whether a function is constant or balanced with a single query. A unique feature of the calculator is the combination of arithmetic and logical functions implemented in hybrid circuits. The calculator is especially suited to interdisciplinary problems that require both numerical solutions and algorithmic decision-making. This project utilizes Qiskit's robust simulation libraries as well as real quantum hardware, making it a highly flexible platform for experimentation, learning, and development in quantum computing.

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Literature review

In quantum computing, information is processed using quantum circuits that are the structural computing platforms for running quantum algorithms. Research work has progressed from the early design, realization, and proof of concept of these circuits to their application in cryptography, optimization, and machine learning. This section reviews the contemporary research literature on quantum arithmetic operations, logical quantum algorithms, and circuit optimization techniques with particular emphasis on their integration into simulators like the quantum calculator. Research into quantum arithmetic operations is mostly oriented toward taking advantage of quantum-mechanical features, such as superposition and entanglement, towards achieving efficient calculations. Initial work presented quantum adders and multipliers that were constructed using techniques such as QFTs and phase estimation.

Recent research on their hybridization has addressed problems that involve decision-making and search methods simultaneously. Such is the incorporation of the Deutsch-Jozsa oracle into Grover's framework that it has been seen to increase the efficiency of specific search tasks. This section highlights the major contributions in the area of engineering, particularly focusing on their development and influence on the research landscape of quantum computing, as summarized in Table 1. The overview emphasizes contributions from the standpoint of their impact on the overall field, illustrating how each innovation may affect future research directions and other aspects of modern quantum computing. Optimization is vital to ensure that a quantum algorithm can run on noisy hardware in an efficient manner. Some of its approaches include gate reduction, qubit assignment, and dynamic compilation, as pointed out in the literature. Qiskit takes both into account and allows one to automatically transpile and optimize circuits according to specific hardware restrictions. More sophisticated techniques, template matching and synthesis, have also supported noise reduction and execution accuracy.

AbuGhanem [1] investigates the performance efficiency of Grover’s search algorithm in superconducting quantum computing. The study examines the challenges associated with scaling Grover’s algorithm and the significant obstacles that must be overcome to make its use effectively achievable in large-scale searching applications.

Shafique et al. [2] provide a detailed overview of quantum computing, defining concepts such as qubits, superposition, entanglement, and more. This article serves as a primer for both novices and expert quantum researchers, outlining standard technologies and applications.

Pokharel and Lidar [3] recommend applying catastrophic error detection and suppression to Grover’s algorithm. Their research demonstrates that improvements in these techniques can statistically enhance the performance of Grover’s algorithm and may even surpass classical search methods.

Al-Bayaty and Perkowski [4] present a new type of Grover diffusion operator that enables the algorithm to target different types of Boolean problems. This change expands the scope and advancement of Grover’s algorithm to more complex computational contexts.

Liu and Liu [5] illustrate how to use Qiskit for running quantum algorithms on IBM’s quantum hardware. Their work provides practical knowledge and serves as a learning resource for the use of practical quantum algorithms.

Nayak et al. [6] offer a rich discussion on the correlation between quantum mechanics and computer science, with a strong focus on algorithmic aspects and practical applications. It is designed to help students and practitioners understand the rapidly evolving domain of quantum computing.

Wu et al. [7] investigate circuit-level improvements to enhance the performance of Grover’s algorithm on quantum computers, leading to significant performance gains and improved efficiency in the use of quantum systems.

Bhoumick et al. [8] provide a hands-on analysis of Grover’s algorithm across various types of quantum processors. The study highlights issues related to each platform and suggests methods for improving performance on each system.

Yang et al. [9] examine current barriers to progress in quantum computing and quantum communication. The authors emphasize the need to establish robust frameworks for scalability, error correction, and security.

Menon and Adhikari [10] assess the current state and future prospects of quantum computing in India. The article focuses on key initiatives and emerging opportunities aimed at strengthening India’s position as a growing player in the global quantum landscape.

Oonishi and Kunihiro [11] implement Shor’s algorithm using a viable approximation of the QFT. The

authors propose a method that improves the effectiveness and practicality of Shor's algorithm on resource-limited quantum systems.

Bhat et al. [12] provide an in-depth evaluation of the fundamentals of quantum computing, the ways in which this understanding can be applied, and key applications across different industry sectors. The work also evaluates the growth of quantum technologies and their potential impact on the future of various industries.

Anwer et al. [13] introduced a technique for generating superposition states through partial negation. This technique demonstrates a simplified variant of the state preparation step, which is useful for a range of applications and scenarios involving quantum algorithms.

There have therefore been several review papers in the literature that have made extraordinary contributions to the theory and development of quantum computing. Most of the material in this area is geared towards people in certain fields, such as physics and computer engineering. This leaves the reader in all freedom. A survey of tools supporting quantum computing and what you might encounter is compiled in this review, which explains from the basics to the most amusing diagrams and figures to ease comprehension. Reading this paper does not require special knowledge on any part. The paper aims to highlight the spectacular advances in quantum computing and guide researchers toward future perspectives.

Materials And Methods

This approach for the quantum calculator seeks to integrate quantum arithmetic, logical quantum algorithms, and circuit optimization techniques into a unified quantum computing framework. It focuses on developing instrumentation capable of executing arithmetic calculations such as addition, subtraction, and multiplication using quantum circuits, as well as incorporating logical quantum algorithms like Grover's Search and the Deutsch-Jozsa algorithm. Further, it emphasizes optimization of quantum circuits to expedite execution, reduce error rates, and increase scalability.

Proposed workflow

1) Problem Initialization: Select a quantum problem (such as Grover's Search or the Deutsch-Jozsa algorithm). Define the input quantum states, required quantum gates, and expected outputs, with optimization objectives focused on minimizing circuit depth, gate count, or both.

2) Quantum Circuit Design in Qiskit: Initialize quantum and classical registers. Construct the quantum circuit using appropriate procedures (e.g., Quantum Fourier Transform where applicable) and design oracles for Grover's, Deutsch-Jozsa, or other quantum algorithms.

3) Quantum Circuit Optimization: Optimize the circuit by eliminating redundant or non-essential gates and replacing costly multi-qubit operations with more efficient alternatives. The optimization is performed using standard, direct-rotation-based quantum simulation techniques.

4) Quantum Simulation and Verification: Perform simulations using Qiskit's Aer backend to verify correctness. Evaluate circuit depth, execution time, resource utilization, and simulation accuracy and report the obtained results.

5) Execution on Quantum Hardware: Execute the optimized circuit on IBM Quantum hardware using the Qiskit Runtime environment. Analyze the measurement outcomes and compare the observed quantum speedup with classical computational results.

6) Assessment of Performance: Assess performance in terms of efficiency, accuracy, scalability, and robustness of the quantum circuits and algorithms. The selected performance parameters are used to evaluate the proposed quantum computation framework and the applied optimization techniques.

7) Real-Life Applications: Apply the optimized quantum algorithms to practical problems such as molecular simulation, climate modeling, and financial optimization.

Circuit depth and optimization

Circuit depth is defined as the number of sequential layers of quantum gates that must be executed in time to complete a circuit. Circuit depth directly influences susceptibility to decoherence and noise on NISQ devices. In this work, circuit depth is used as a primary performance metric alongside gate count and execution time. QFT-based arithmetic circuits introduce multiple controlled-phase rotations, which can increase circuit depth if left unoptimized. To address this, Qiskit's transpilation and optimization passes - such as gate cancellation, basis-gate decomposition, and qubit layout optimization - are applied. These techniques significantly reduce circuit depth while preserving functional correctness.

IBM Quantum hardware description

Experiments are conducted using IBM Quantum platforms accessed via Qiskit. IBM Quantum hardware is based on superconducting transmon qubits implemented using Josephson junctions operating at cryogenic temperatures. Qubits are controlled and measured using microwave pulses, and device topology is defined by fixed qubit coupling maps. The native gate set consists primarily of single-qubit rotation gates and two-qubit controlled-NOT (CNOT) gates. Practical execution is constrained by gate error rates, readout errors, coherence times (T1 and T2), and cross-talk. These limitations motivate aggressive circuit optimization, particularly depth reduction, to improve execution fidelity.

Results

The proposed quantum calculator is evaluated using both simulation and real hardware execution. Arithmetic operations such as addition, subtraction, and multiplication are implemented using QFT-based circuits and verified through measurement statistics obtained from Qiskit Aer simulators. Logical algorithms including Grover's Search and the Deutsch-Jozsa algorithm are evaluated using oracle-based circuits. Hybrid circuits combining arithmetic computation with logical decision-making are also constructed. Simulation results confirm correct functional behavior, while hardware execution demonstrates feasibility on NISQ devices for small problem sizes. Circuit depth and gate count analyses show measurable reductions after optimization.

Experimental setup

1) Hardware Environment: The algorithms will run in quantum simulators such as IBM Quantum. These platforms grant access to NISQ processors and efficient simulation tools.

2) Simulation Setups: In this test setup, Qiskit, an open-source quantum development toolkit, with Qiskit Terra, is used to construct quantum circuits and conducts optimizations like transpilation, whereas Qiskit Aer accurately simulates quantum circuits to make an estimation of the efficiency of the circuit.

3) Assessment Criteria: The performance of the hybrid arithmetic-logical quantum circuits is measured by the following criteria:

• Circuit Depth: This indicates the number of layers of sequential gates; an important measure of how susceptible a circuit can be to decoherence.

• Gate Count: This measures the total number of quantum gates, including single-qubit and multi-qubit operations.

• Execution Time: This measures all of the time required for executing the circuit - either on simulators or real quantum hardware.

• Error Rates: This measures the impact of quantum noise, errors in the gates and decoherence effects to the total fidelity of the circuit.

The results and analysis focus on evaluating the performance of this approach using the following methods:

Quantum Addition: Figure *1* shows that the quantum addition can be performed between two numbers and one quibit. It demonstrates that the total amount of frequency must be utilized to perform this operation, as illustrated in the example below.

Example: If first_num = 3 and second_num = 4 with num_qubits = 5, then the resultant value = 7.

Possible results and their frequencies:

Bitstring: 00011, Frequency: 728, Result: 3

Bitstring: 00111, Frequency: 100, Result: 7

Bitstring: 11111, Frequency: 86, Result: 31

Bitstring: 00101, Frequency: 48, Result: 5

Bitstring: 01111, Frequency: 20, Result: 15

Bitstring: 10111, Frequency: 13, Result: 23

Bitstring: 00100, Frequency: 9, Result: 4

Bitstring: 00001, Frequency: 5, Result: 1

Bitstring: 10101, Frequency: 4, Result: 21

Bitstring: 11101, Frequency: 3, Result: 29

Bitstring: 01001, Frequency: 2, Result: 9

Bitstring: 00110, Frequency: 2, Result: 6

Bitstring: 00010, Frequency: 2, Result: 2

Bitstring: 11100, Frequency: 1, Result: 28

Bitstring: 01101, Frequency: 1, Result: 13

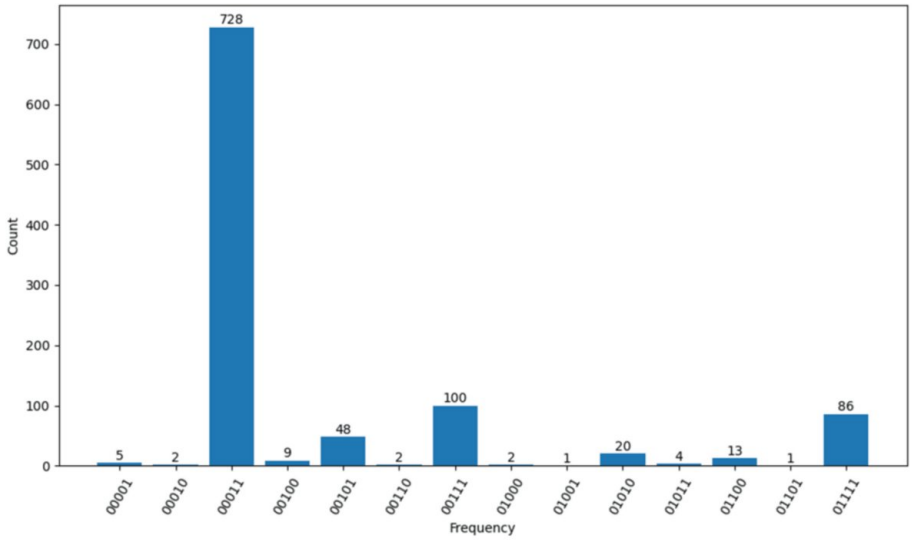

FIGURE 1: Possible results and their frequencies of quantum addition

Quantum Substraction: Figure *2* shows that quantum subtraction can be performed between two numbers using one qubit. It demonstrates that the total amount of frequency must be utilized to perform this operation, as illustrated in the example below.

Example: If first_num = 6 and second_num = 3 with num_qubits = 2, then the resultant value = 3.

Possible results and their frequencies:

Bitstring: 01, Frequency: 448, Result: 1

Bitstring: 10, Frequency: 431, Result: 2

Bitstring: 00, Frequency: 107, Result: 0

Bitstring: 11, Frequency: 38, Result: 3

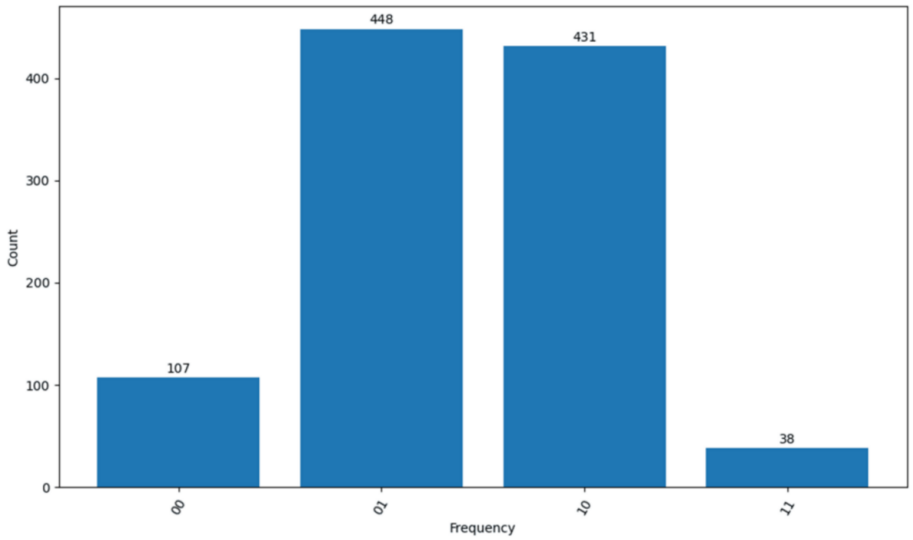

FIGURE 2: Possible results and their frequencies of quantum subtraction

Quantum Multiplication: Figure *3* shows that quantum multiplication can be performed between two numbers using one qubit. It demonstrates that the total amount of frequency must be utilized to perform this operation, as illustrated in the example below.

Example: If first_num = 4 and second_num = 6 with num_qubits = 3, then the resultant value = 24.

Possible results and their frequencies:

Bitstring: 011000, Frequency: 1024, Result: 24

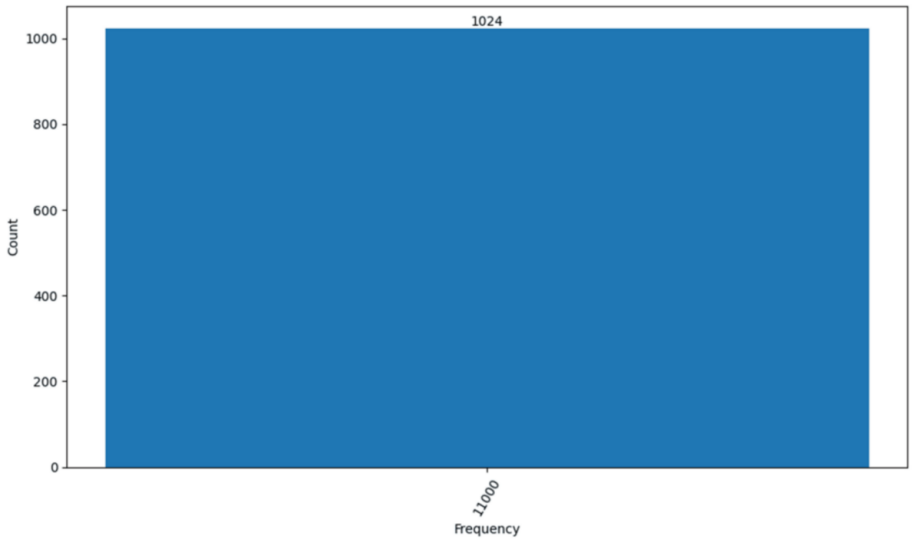

FIGURE 3: Possible results and their frequencies of quantum multiplication

Grover's Search Algorithm: Figure *4* shows that Grover's search can determine whether an element is present in a list. If the element is present, the corresponding qubits show a higher probability, as illustrated in the example below.

Example: If number of qubits = 4 and marked state = 6, then the resultant with respective circuit is 471.

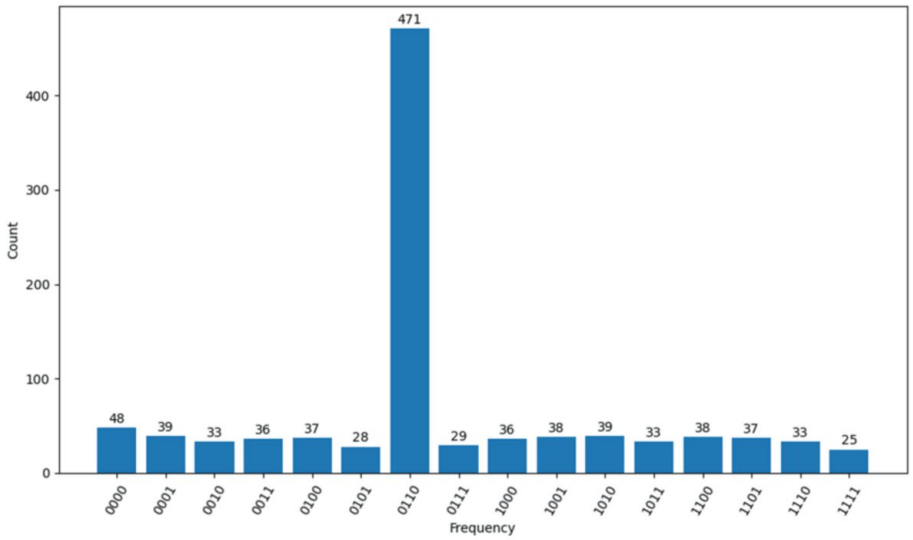

FIGURE 4: Possible results and their frequencies of marking state is “5”

Figure *5* shows that the Grover’s search circuit can perform the above operation by searching for an element in the circuit.

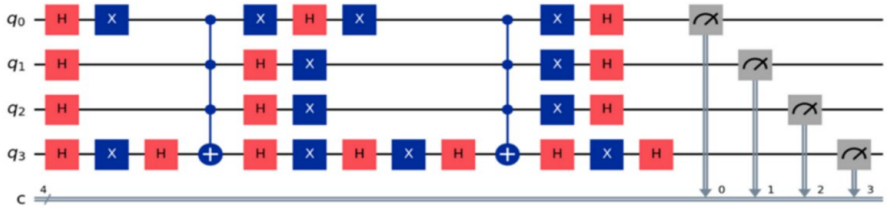

FIGURE 5: Grover’s search circuit

Deutsch-Jozsa Algorithm: Figure *6* shows that the Deutsch-Jozsa algorithm can be used to check whether the circuit is balanced or constant. If the circuit is balanced, a balanced operation is performed, as illustrated in the example below.

Example: If number of qubits = 3 and function state = balanced, then the resultant with respective circuit is 1024.

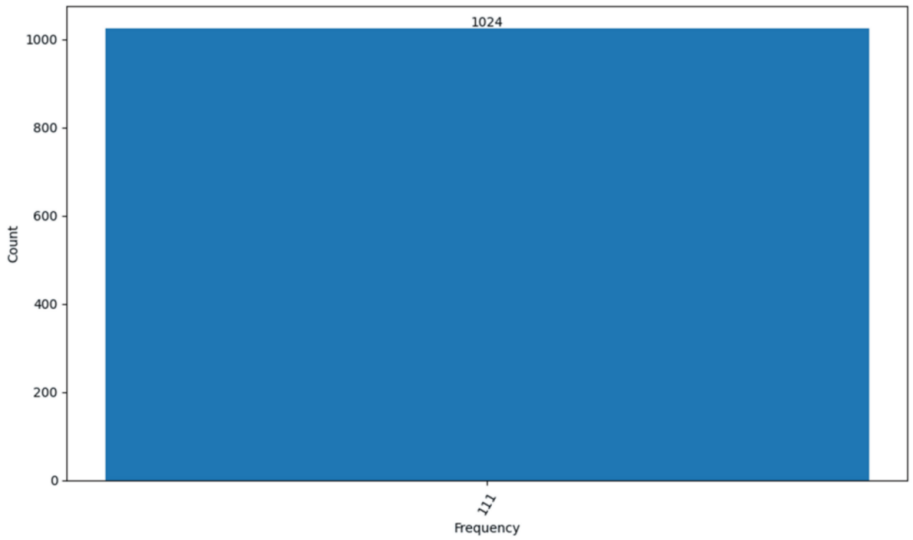

FIGURE 6: Possible results and their frequencies of function state is "balanced"

Figure 7 shows the Deutsch-Jozsa circuit based on the balanced operation described above.

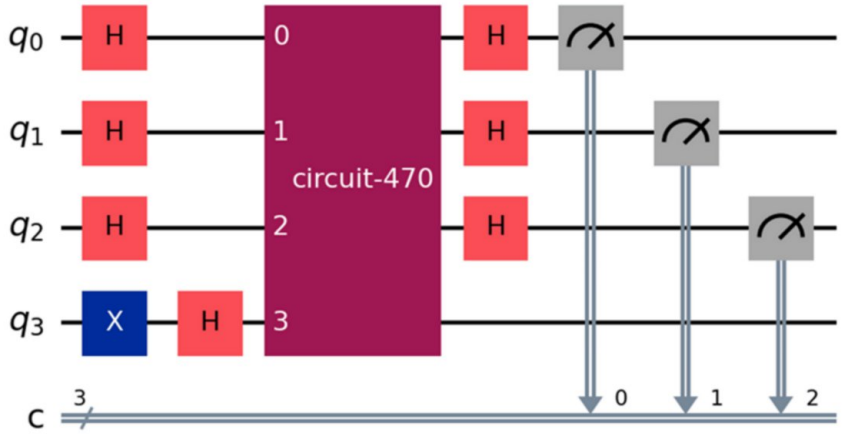

FIGURE 7: Deutsch-Jozsa circuit with "balanced" function state

Figure 8 shows that the Deutsch-Jozsa algorithm can be used to check whether the circuit is balanced or constant. If the circuit is constant, a constant operation is performed, as illustrated in the example below.

Example: If number of qubits = 4 and function state = constant, then the resultant with respective circuit is 1024.

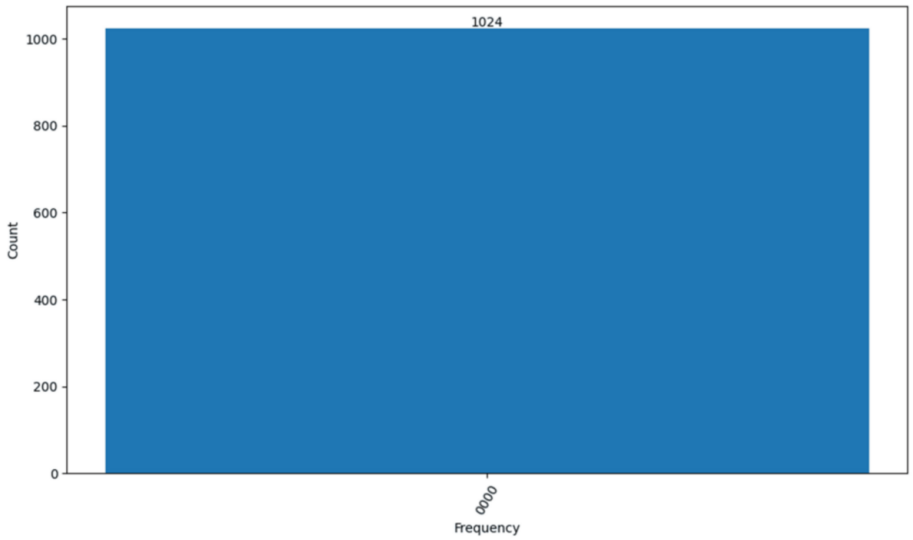

FIGURE 8: Possible results and their frequencies of function state is "constant"

Figure *9* shows the Deutsch-Jozsa circuit based on the constant operation described above.

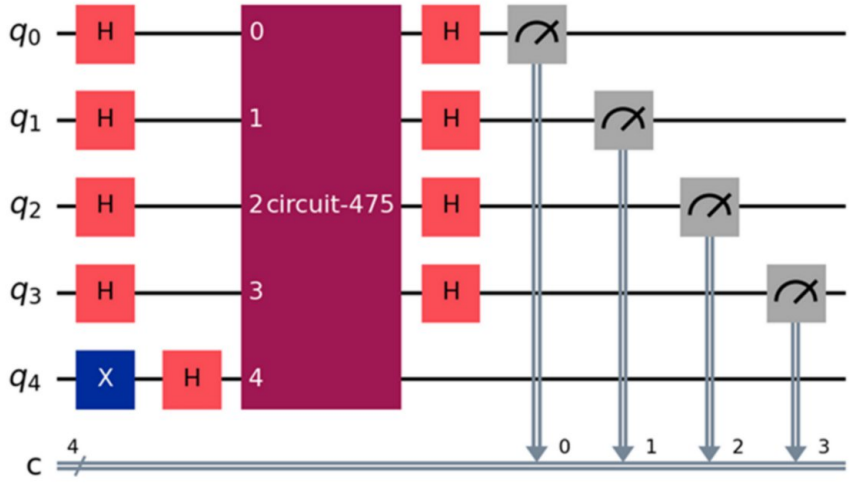

FIGURE 9: Deutsch-Jozsa circuit with "constant" function state

Deutsch-Jozsa with Grover's Search Algorithm: Figure *10* shows that the Deutsch-Jozsa algorithm with Grover's search can be used to check whether the circuit is balanced or constant. If the circuit is balanced, a logical operation is performed by searching for an element; otherwise, the operation is discarded in the constant state, as illustrated in the example below.

Example: If number of qubits = 3, marked state = 6, and function state = balanced, then the resultant with respective circuit is 138.

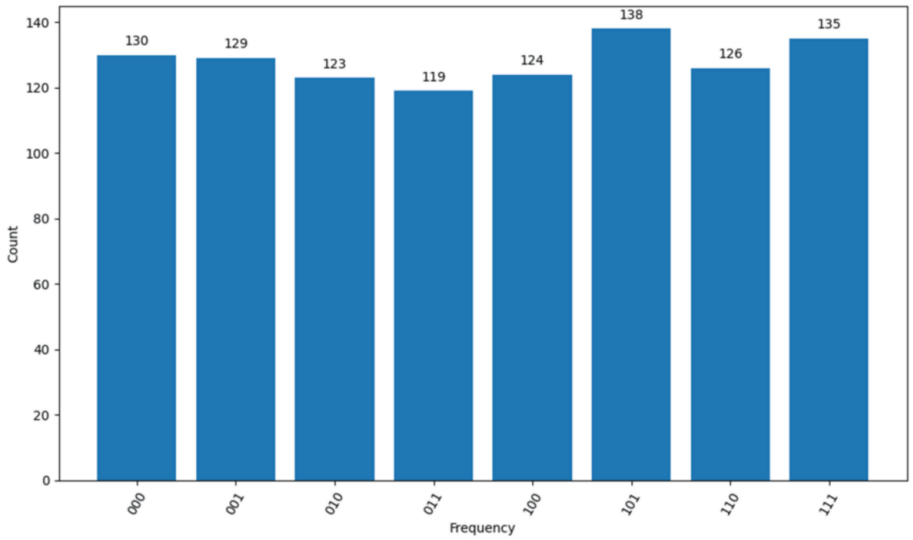

FIGURE 10: Possible results and their frequencies of marking state is "6"

Figure *11* shows the Deutsch-Jozsa algorithm with Grover's search circuit, based on the balanced operation described above.

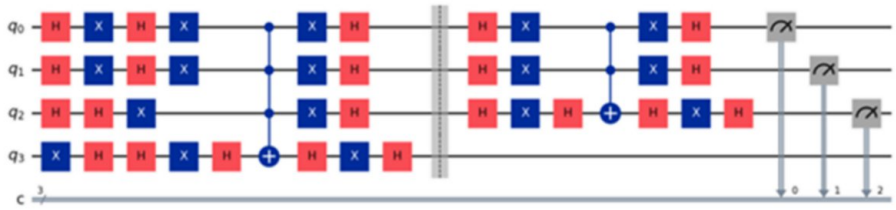

FIGURE 11: Grover's search with the Deutsch-Jozsa circuit with "balanced" function state

Discussion

This study aims to evaluate the operational ability and efficiency potential of the proposed quantum calculator in terms of combining arithmetic and logical quantum functions developed in Qiskit. The experimentation was undertaken using quantum simulators and NISQ hardware accessed via IBM Quantum through the cloud. The analysis was strongly intended to evaluate how circuit complexity, duration of operation, and noise play into the two central areas of performance, namely arithmetic and logical functions, where these hybrid circuits combine both arithmetic and logical functions.

First, the Deutsch-Jozsa algorithm was used to classify a set of Boolean functions that asked the question if the function was either constant or balanced. The simulation results demonstrated that the algorithm theoretically could offer exponential acceleration in identifying function type in only one run, in contrast to classical algorithms where multiple queries are needed. Simultaneously, the Grover's algorithm was assessed through unstructured search where a particular element needed to be extracted from a broad domain, and the quantum approach had clear advantages, where significantly fewer iterations needed to be completed to arrive at the solution, as predicted the classical brute-force approach anticipated the quadratic acceleration. When assessing the arithmetic components of the calculator, we constructed quantum circuits for addition, subtraction, and multiplication using modular quantum arithmetic, controlled operations, and, for example, the quantum Fourier transform. The simulations indicated that these circuits could perform precise arithmetic operation with a small depth and a small number of quantum gates for small inputs. Like other NISQ systems, the amount of resources we used for these registers and circuits grew exponentially with the input size.

One of the main highlights of the evaluation was hybrid circuits, which are hybridizations of arithmetic

logic and quantum algorithms (such as Grover's search). We created a number of hybrid circuits that allow evaluation in scenarios where computational numbers (logic) and algorithms (decisions) coexist into a single framework. The evaluation of these circuits made use of a number of metrics, such as the depth of the circuits, number of unique gates, total execution time and error rates. Even though hybrid circuits add complexity, when we used the transpilation and optimization tools in Qiskit to design hybrid circuits, we could limit unneeded resource usage. We ran a number of simulations in Qiskit Aer using simulated noise models to manage the effects of decoherence and gate infidelity during execution. When we ran the execution on actual devices, we confirmed what we saw in simulation; hybrid circuits are fine in practice, but are mostly limited by noise, and require more optimization and/or error correction techniques.

Conclusions

This paper concludes that quantum computing framework with qiskit for circuit optimization, represents a big increase in improving the workings of quantum computing for real-world issues. The system promotes a minimum number of resources consumed by the quantum circuits that perform mathematical computations, logical procedures, and error correction, resulting in an increased speed and precision. A hybrid approach that combines quantum and classical methods achieves effectiveness in such demanding operations as cryptographic key extraction, and logistics optimization. The proposed approach implemented seeks to enhance flexibility and extensibility in line with the growth of quantum technologies and the thought to be true for many realities in such other domains as cryptography, healthcare, and finance. Eventually, focusing on decreasing quantum circuit depth, improving gate fidelity, and optimizing actual hardware will support much more reliable, faster, and resource-efficient operations in quantum computing, thereby allowing for more widespread adoption of quantum technologies in solving complex real-world contexts.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Milind B. Waghmare

Acquisition, analysis, or interpretation of data: Milind B. Waghmare, Nayan S. Thorat, Kamlesh A. Waghmare, Prashant N. Chatur

Drafting of the manuscript: Milind B. Waghmare, Nayan S. Thorat, Kamlesh A. Waghmare, Prashant N. Chatur

Critical review of the manuscript for important intellectual content: Milind B. Waghmare, Nayan S. Thorat, Kamlesh A. Waghmare, Prashant N. Chatur

Supervision: Milind B. Waghmare, Nayan S. Thorat, Kamlesh A. Waghmare, Prashant N. Chatur

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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Experimental dataset is available on
https://drive.google.com/drive/folders/1dz2CFqQgLaA8tvLWeV9S5aSuVBzvt89X?usp=sharing

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